Energy Harvesting in Electric Power Systems for Data Communication Purposes

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***Abstract*—Aiming to illuminate the path towards integrating energy harvesting (EH) technologies into modern electric power systems, thereby enabling more efficient and sustainable energy solutions, this paper explores energy harvesting within electric power systems and points out its potential to power data communication purposes. In this sense, we examine the overarching principles of EH in these systems, spotlighting both the merits and limitations associated with energy extraction across varying voltage levels and electric signal frequency bands. Central components of EH devices, alongside a spectrum of harvesting methodologies, are thoroughly reviewed. Also, we showcase a case study that provides a quantitative assessment of EH potential in electric power systems. The manuscript culminates in a forward-looking analysis of EH, considering emerging technologies that promise to redefine the landscape. These include integrating hybrid power line and wireless systems, strategies for optimal power allocation, enhancements in physical layer security, the innovative concept of negawatts, advancements in harvesting circuit designs and applying non-orthogonal multiple access techniques.**

***Index Terms*—Energy harvesting, power line communication, electric power systems, wasted energy.**

I. INTRODUCTION

Electric power systems have been recognized as the most complex artificial systems built by human beings. They were conceived to generate, transmit, and distribute energy from distant high-power power generation plants to the end-users (consumers) using a mains frequency of 50 or 60 Hz because the purpose was to reach long distances. However, there is a remarkable change from this model because of the increasing and massive use of electronic-based equipment that is pushing forward the introduction of several energy sources, mainly renewable, into the grid close to or by consumers, who can eventually become prosumers. In this sense, energy efficiency and, most importantly, sustainability are important issues to be addressed. While energy efficiency focuses on how efficient energy is to perform work, sustainability provides adequate, reliable, and affordable energy without jeopardizing energy needs or future generations.

It is well-established that the use of non-ideal and electromagnetically unshielded conductors to transmit and deliver electric energy. Consequently, there are thermal (ohmic or conductor), dielectric, and radiation losses. Ohmic losses are the leading and most significant technical losses on electric power systems, reaching up to 7.5% of the produced electricity [1] while the other losses are insignificant. However, the increasing demand for energy consumption is bringing attention to the less insignificant losses. For instance, recent contributions have pointed out that energy can be harvested from the electromagnetic field generated by the mains frequency in the transmission lines.

Moreover, the increasing and massive presence of nonlinear loads is becoming responsible for large-scale re-injections of energy at different frequencies into electric power systems due to their interactions with electric power systems. This phenomenon, combined with the antenna behavior of power lines, results in wasted energy spread over the spectrum in power lines; see [2] for details. This spectrum content, distinct from the mains frequency content, represents time-varying electric signals in the frequency domain. Consequently, they result in time-varying electric and magnetic fields, from which energy can be harvested through capacitive or inductive circuits specifically designed to better take advantage of it. In this sense, the energy reuse, or the Energy Harvesting (EH), of this kind of wasted energy can improve the energy efficiency of electric power systems and, most importantly, sustainability mainly for dealing with the highly massive number of Internet of Things (IoT) devices spread over the earth in the coming years.

Energy harvesting in electric power systems mainly based on the reuse of wasted energy associated with electric signals is promising because the reuse of such wasted energy also benefits Power Quality (PQ). Indeed, disturbances in electric signals result in several PQ problems; consequently, their removal can remarkably long-lasting benefit electric power systems. In this sense, this paper focuses on distinct aspects of EH in electric power systems and how it can help improve sustainability, PQ, and supplying energy to data communication devices. In this regard, the following contributions are presented:

- To provide a comprehensive discussion on energy harvesting in electric power systems, bringing attention to both typical energy sources in terms of their origins and

This work was supported in part by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) under Grant 001, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) under grants 404068/2020-0 and 314741/2020-8, Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) under grants APQ-03609-17, TEC-PPM 00787-18, and APQ-04623-22, and Instituto Nacional de Energia Elétrica (INERGE).

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Digital Object Identifier (DOI): 10.14209/jcis.2024.6

common EH approaches. Also, the inclusion of Wasted Electric Signals (WESs) as a source of energy for EH.
- To introduce essential aspects of electric- and magnetic-field-based EHs using typical classifications of the electric power systems in terms of voltage levels and frequency bands of electric signals.
- To describe some critical aspects of EH devices and three main harvesting methods. Also, a case study of the quantitative evaluation of EH is presented.
- To discuss future trends of EH in electric power systems with upcoming technologies based on hybrid communications, optimal power allocation, physical layer security, negawatts, harvesting circuitry, and Non-Orthogonal Multiple Access (NOMA).

The rest of this paper is organized as follows: Section II introduces the fundamentals of energy harvesting in electric power systems; Section III discusses the EH in terms of the voltage level and the frequency band of electric signals; Section IV focuses on describing the harvesting methods and the main parts of an EH device circuitry, while Section V brings a quantitative analysis of the harvested power in a low-voltage environment. The future trends about EH in electric power systems are then covered in Section VI, and Section VII states concluding remarks. Finally, Table I lists the acronyms.

II. ENERGY HARVESTING

Energy harvesting is defined as extracting any form of energy from an external source, which can be *natural* or *artificial*, and converting it to electricity. The natural sources are already in the environment where the EH device is immersed, generating environmental signals, such as sunlight, wind, and geothermal heat. On the other hand, artificial sources require the installation of EH devices next to them. These sources are consequences of human or system activities that result in non-environmental signals, e.g., human motion, system vibration, and electromagnetic radiation from radio frequency (RF) devices or broadcasting radio stations [3]. Regardless of their types, the primary energy sources for performing EH reported in the literature are light, heat, motion, and electromagnetic radiation [3]–[8], being the focus of this paper on the latter.

A. Electromagnetic Radiation

It is established that radio-frequency EH can be subdivided into two distinct approaches according to the source of energy: *ambient EH*[1] or *dedicated EH* [4]. In the former, an EH device harvests its energy from a source that is already present in the environment, but it is not intended to deliver energy, which can be accomplished through the electromagnetic waves of RF signals generated by TV, radio stations (e.g., AM and FM), WiFi devices, Bluetooth devices, cellular base stations, among others. On the opposite, the latter aims at energizing a particular EH device through directional energy transfer in a specific frequency band, e.g., one of the industrial, scientific, and medical (ISM) frequency bands - and the EH device has certainty about the existence of another device that is capable of delivering continuous energy. At this point, it is important to emphasize that the definition of ambient and dedicated EH approaches from radio-frequency EH can be extended to more general applications and environments from a telecommunication perspective. In other words, the ambient EH approach will be used to refer to the EH applied to the additive noise of data communication media, while the dedicated EH approach will stand for the EH performed in both the additive noise and the free-of-noise (FoN) received signal from data communication media.

Nowadays, the opportunity of harvesting energy from wireless communication (WLC) sources (i.e., from electromagnetic waves) based on EH has been investigated due to the possibility of creating wireless self-sustainable networks [4], [9],

TABLE I: List of acronyms.

Acronym	Meaning
AC	Alternating Current
ARIB	Association of Radio Industries and Businesses
BB-PLC	Broadband-PLC
CENELEC	EU Committee for Electrotechnical Standardization
DC	Direct Current
E-field	Electric Field
EEH	Electric Field Energy Harvesting
EH	Energy Harvesting
FCC	Federal Communications Commission
FoN	Free-of-Noise
HV	High-Voltage
IoT	Internet of Things
ISM	Industrial, Scientific, and Medical
LV	Low-Voltage
M-field	Magnetic Field
MEH	Magnetic Field Energy Harvesting
MV	Medium-Voltage
NB-IoT	Narrowband-IoT
NB-PLC	Narrowband-PLC
NOMA	Non-Orthogonal Multiple Access
PLC	Power Line Communication
PLS	Physical Layer Security
PQ	Power Quality
RF	Radio Frequency
SG	Smart Grid
SNR	Signal-to-Noise Ratio
UNB-PLC	Ultra-Narrowband-PLC
WEH	WES EH
WES	Wasted Electric Signal
WLC	Wireless Communication

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[1] Here, the terms ambient and natural are not related to each other, such that the former is associated with a radio-frequency EH approach and the latter indicates the origin of the source of energy.

and it can allow 5G and 6G data networks to supply energy to a large number of IoT devices. However, harvesting energy from electromagnetic waves over time may not give constant power to an EH device due to propagation issues, such as reflection, scattering, and diffraction. Therefore, when there is a necessity for the continuity of energy supply to a device, the importance of electric power systems is undeniable [10]. In these systems, the energy supply can be mainly obtained from the Alternating Current (AC) mains signal and, as it is emphasized in this paper, EH can be applied to disturbances generated by the interactions between electric power systems and non-linear loads as well as by the RF signals induced into unshielded power lines. Plentiful electric and magnetic fields generated from AC mains signal and disturbances are always present in the vicinity of the energized and electromagnetically unshielded power lines, being the disturbances appealing and emerging sources of energy for performing EH.

Energy harvesting in electric power systems is usually investigated for powering condition monitoring sensors. Besides the natural sources of energy, the artificial ones that can be used for EH, exclusively in electric power systems, are the Electric Field (E-field) and Magnetic Field (M-field) generated by the AC mains signal [11], [12]. These fields are promising for EH purposes due to their strengths and continuous presence in the vicinity of energized power lines. In addition, another interesting source of energy is the combination of disturbances such as harmonics, interharmonics, supraharmonics, transients, and RF induced signals that are added to the AC mains signal, and is being called WES. Taking advantage of or reusing the energy associated with WESs can benefit both the environment and the energy efficiency of electric power systems. One is related to the reduction of global greenhouse gas emissions released during the combustion of fossil fuels, whereas the other is associated with the reduction of power quality issues since disturbances in electric signals are one of the main sources of power quality degradation in electric power systems. The existing energy in WESs can be harvested by means of the electric or magnetic fields generated by the components of the electric signal different from the AC mains frequency and, thus, it is also considered an artificial energy source. In other words, EH from WES is similar to the aforementioned E-field and M-field ones; however, it distinguishes from them by exploiting the energy contained in the frequency spectrum of electric signals outside the AC mains frequency.

The EH from artificial sources in electric power systems is performed by exploiting the E-field and M-field produced by electric signals. However, the EH from natural sources in electric power systems is performed by means of environmental signals, which do not originate from electric signals. Therefore, natural sources can be found in any other context, and the focus of this paper will be on the specific ones generated by electric signals, the artificial sources. The main requirements for performing EH from artificial sources are controllability and predictability, see Table II, in which the design of the electric power system is considered to be known and remains unchangeable over time. *Predictability* refers to the degree to which the energy availability of the source approximates having periodic dynamic during a time interval (e.g., an hour, a day, a week, and so on), while *controllability* refers to the source's capacity of supplying energy for EH when demanded. On the one hand, a controllable source is capable of providing harvested energy whenever demanded, and, as a consequence, the energy availability does not need to be predicted. On the other hand, an uncontrollable source must have its energy harvested whenever energy is available, thus the energy availability of this kind of source must be predicted whether it is possible. In this regard, a prediction model that forecasts energy availability can be used to assist the dynamic of the recharging cycle [13].

TABLE II: Artificial sources for EH in electric power systems.

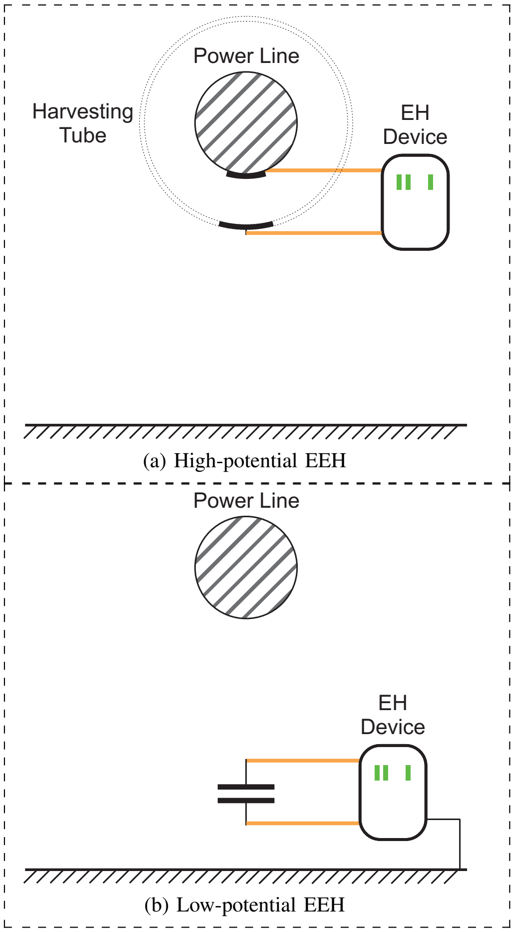
Source	Characteristics	Literature
E-Field	Controllable and predictable	[14]–[23]
M-Field	Controllable and predictable	[24]–[31]
WES	Partially controllable/predictable	[2], [32]–[37]

In the following subsections, the E-field and M-field artificial sources of energy are detailed, highlighting the theoretical foundation behind the generation of this kind of energy in electric power systems. Also, the main approaches for using these artificial sources for powering EH devices are discussed, and the WES-based EH is introduced.

1) Electric Field: The Electric Field Energy Harvesting (EEH), or capacitive energy harvesting, is the most preferable kind of EH to supply energy to condition monitoring sensors in overhead transmission lines. A time-varying E-field is produced by the AC mains voltage signal presence on a power line even without a current flow, and according to Maxwell's equation, a time-varying E-field produces a displacement current that can be used to charge a capacitor composed of two conducting plates, with the air being used as the dielectric. When this capacitor is connected to a load, there will be a current flowing through it due to the potential difference. Consequently, EEH is accomplished.

Based on the fact that the intensity of the stray E-field surrounding the power line decreases with the increase of the distance from the power line, EEH can be subdivided into high- and low-potential approaches. In the former, the capacitor is near the power line, while in the latter, it is near the ground. Figs. 1(a) and 1(b) illustrates the high- and low-potential EEH, respectively. The high-potential approach assumes that the EH device is inside the harvesting tube, which is coated with an electrical conductor material and clamped to the power line. In this approach, the capacitor can be either produced by the equivalent capacitance between the power line and the harvesting tube or formed by two plates, in which one is connected to the power line and the other is in the harvesting tube. If the two plates are adopted, then two equivalent capacitances are created: i) between the two plates and ii) between the lower plate of the capacitor and the ground. In the low-potential approach, the EH device is connected to the two plates of the capacitor and grounded, resulting in two equivalent capacitances: i) between the power line and the upper plate of the capacitor and ii) between the two plates.

Note that, in both approaches, the two equivalent capacitances are in series, thus they are used as voltage dividers. It is noteworthy to mention that if the voltage signal is a Direct Current (DC) one, then there will be a constant E-field, which does not generate a displacement current, and EEH will not be produced.



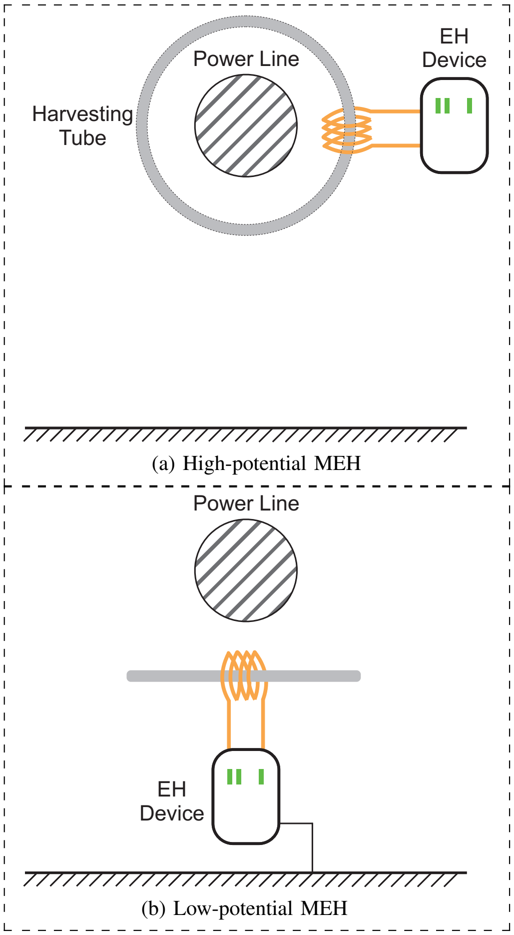
(a) High-potential EEH

(b) Low-potential EEH

Fig. 1: E-field energy harvesting.

2) Magnetic Field: The Magnetic Field Energy Harvesting (MEH), or inductive energy harvesting, consists of a coil that is wired in a ferromagnetic core. The core is responsible for concentrating the time-varying magnetic flux from the stray M-field produced by the current flowing in the power line. According to Maxwell's equation, the time-varying magnetic flux in the core induces a voltage between the terminals of the coil. When the coil terminals are connected to a load, a current flows through it, and MEH is accomplished. The time-varying M-field is produced by the oscillation associated with the AC mains current signal flowing through a power line. In this case, the flowing current is a necessary condition, and the variations experienced in the AC current signal result in the variations of the M-field. For instance, the connection and disconnection of loads and other similar events (e.g., lightning and failures) in electric power systems may result in large amplitudes for the AC current signal; therefore, the M-field around power lines can vary greatly from time to time.

Since the intensity of the M-field decays with the increasing distance from the power line, MEH can be subdivided into high- and low-potential approaches, according to the proximity between the ferromagnetic core and the power line. In the former, the ferromagnetic core usually has a ring shape and is clamped in the section of the power line through the harvesting tube while the latter adopts the conventional cylindrical-shaped ferromagnetic core, which is placed off the power line. These approaches are shown in Fig. 2, where the high- and low-potential MEH can be seen, respectively, in (a) and (b). Alternative ferromagnetic core shapes and their influence on the magnetic flux concentration were studied in [25]; however, it is important to emphasize that a DC current signal generates a constant M-field, which results in constant magnetic flux in the core that does not induce voltage between the terminals of the coil and MEH is not accomplished.



(a) High-potential MEH

(b) Low-potential MEH

Fig. 2: M-field energy harvesting.

3) Wasted Electric Signal: Both EEH and MEH were investigated in electric power systems aiming at harvesting the energy associated with AC mains voltage and current signals, respectively. However, it is possible to supply energy from the components of electric signals outside the AC mains frequency, which may own enough energy to supply low-power consumption devices (e.g., IoT devices) [2], [37]. Disregarding the AC mains frequency and considering a telecommunications perspective, the covered frequency spectrum content that is eligible for EH purposes comprehends the power line communication (PLC) additive noise [38], which is equivalent to the disturbances in electric signals. The well-known disturbances of the AC mains signal are harmonics, interharmonics, supraharmonics, and transients as well as RF signals induced into power lines because their majority is electromagnetically unshielded. These disturbances are seen as sources of power quality issues in the electric power systems and are also considered unwanted interference to PLC systems. In this sense, the recovery of the PLC additive noise's energy, namely WES EH (WEH), can be useful for improving power quality in electric power systems, supplying energy to PLC systems, and enhancing the data communication system performance. The definitions of WES and WEH to denote, respectively, the disturbances in an electric signal and their EH highlight the fact that the energy associated with disturbances in electric signals has been wasted, and, as a consequence, it is free of charge. In the manner it was defined, the ambient EH approach applied to power lines corresponds to the harvesting of the PLC additive noise by an EH device, which is the same as WEH. On the other hand, the use of a dedicated EH approach in power lines results in the harvesting of both PLC additive noise and FoN received signal.

III. CLASSIFICATION OF ENERGY HARVESTING

This subsection discusses two perspectives for classifying EH in electric power systems and highlights important advantages and drawbacks of EEH, MEH, and WEH. It is expected that electric power systems present distinct characteristics and face different problems in terms of construction, geographical coverage, and purpose. Also, electric signals in these systems present a variety of components on their spectrum content depending on the frequency band. Therefore, EH in electric power systems is first classified according to the voltage levels of the AC mains voltage signal, and then the frequency bands of the spectrum content of electric signals are used to classify the EH.

A. Voltage Level

The classification of electric power systems based on the voltage level, see Table III, is also applied to classify EH in these systems. In short, the EEH is widely studied in the High-Voltage (HV) [14]–[17] and Medium-Voltage (MV) [17]–[20] power lines while the MEH is mostly investigated in the HV [24]–[27] and Low-Voltage (LV) ones [29]–[31]. Different from EEH and MEH, WEH is focused on LV power lines [2], [36], [37].

TABLE III: Voltage level classification of electric power systems [39].

Classification	Voltage Level	Geographical Range
HV	$35 - 230$ kV	< 500 km
MV	$1 - 35$ kV	$5 - 25$ km
LV	< 1 kV	< 500 m

1) High-voltage level: HV electric power systems, or electric power transmission systems, as illustrated in Fig. 3, operate with AC mains voltage levels typically in the order of tens to hundreds of kilovolts ($35 - 230$ kV), covering distances from several dozen to hundreds of kilometers (up to 500 km), being responsible for connecting power generation stations to distribution stations. In these levels, power lines have energy losses due to heating, leakage, and corona effects [40]. The transmission lines are usually overhead (aerial) and composed of electromagnetically unshielded power lines.

Fig. 3: Electric power transmission system.

The most investigated kinds of EH in HV power lines are the EEH [14]–[17] and MEH [24]–[27] due to the high amplitudes associated, respectively, with AC mains voltage and current signals. Furthermore, the use of WEH (i.e., the EH of PLC additive noise) may not be practical in these systems due to the expensive coupling related to the use of special components necessary to withstand high differential voltages [41]. However, the impact of large-scale penetration of distributed generation in these systems may result in a power quality issue due to the harmonics and interharmonics presence, in which WEH can take advantage of it by harvesting the energy present in them. Consequently, this voltage level constitutes the most expensive and complex environment to deal with; however, transmission lines may be potential candidates for WEH in the future because of the numerous presence of distributed and renewable power plants connected to electric power transmission systems.

2) Medium-voltage level: Electric power distribution systems in the MV level have AC mains voltage levels up to dozens of kilovolts ($1 - 35$ kV), spanning a few kilometers ($5 - 25$ km). They connect the distribution stations to the pole-mounted transformers and are used to supply electric energy to rural areas, cities, industries, and companies [40]. The MV power lines can be underground or overhead ones, being the overhead power lines electromagnetically unshielded and widely deployed, while the underground power lines are typically shielded for corrosion resistance and mainly used in high-density downtown areas. A picture of an overhead electric power distribution system is shown in Fig. 4.

In terms of EH, MV electric power systems are mostly investigated for EEH [17]–[20] rather than MEH [28]. Indeed, a hybrid EH solution composed of thermal, mechanical, and M-field EHs was designed to harvest a constant amount of energy from a MV busbar over time; see [28]. Similar to the HV power lines, the AC mains voltage signal in the MV power lines can be predicted as they are designed to operate at a specific level and, disregarding natural or artificial

Fig. 4: Electric power distribution system.

incidents, are not subject to great variations over time. Also, MV electric power systems usually encompass the distributed generation and are cheaper to perform coupling than the HV ones [41], which can make WEH more interesting in the MV electric power systems than in HV ones. For instance, [32] investigated the WEH potential of MV power lines in the urban and rural environments and showed the usefulness of the energy contained in the PLC additive noise for feeding low-bit-rate devices.

3) Low-voltage level: Electric power distribution systems in the LV level employ AC mains voltage levels below a kilovolt (< 1 kV), running over distances of a few hundred meters (up to 500 m). These systems connect the pole-mounted transformers to individual households and appliances and electrical equipment in predial, residential, industrial, and commercial electrical circuits [40]. The LV power lines are, in general, electromagnetically unshielded and are used in indoor (e.g., residencies and buildings), outdoor (from transformers to individual households), and in-vehicle facilities (e.g., car, ship, and airplane).

In this context, MEH was adopted in the past due to size constraints [20], while the EEH uses are rather recent [21]. Due to the low potential of EEH in LV, the EH device would have a dimension that could not be interesting to harvest a sufficient amount of energy for feeding it [11]. This was overcome by either placing a conductive sheath around the power line or using a multi-layer harvesting structure to increase the displacement current obtained from the stray E-field [21]–[23]. As a disadvantage, the MEH in LV electric power systems is much more subject to time variations due to the dynamic of loads connected to them. In other words, the variety of loads, as well as their dynamics (e.g., connection/disconnection), make the AC current flowing through LV power lines less predictable in terms of voltage level. However, the literature shows that MEH can be applied to both indoor and outdoor facilities [29]–[31] while the same can be stated for EEH [21]–[23].

Due to the necessity to attenuate the AC mains signal, WEH is mostly exploited in LV power lines [2], [36], [37]. In other words, the connection between the EH device and either one of HV or MV power lines demands a more complex and expensive coupling circuit than the one for LV power line. Therefore, the WEH may offer a cost-effective solution because the physical connection can be easily established between the EH device and the power outlet in an LV indoor facility [2]. Moreover, the interactions of non-linear loads (e.g., appliances, motors, and others) and the LV electric power systems generate disturbances, and, consequently, a high amount of energy is expected outside the AC mains frequency, making it more convenient to harvest the energy of WESs near the loads, which are mainly connected to LV power lines [41]. In vehicular environments, the power is delivered from a DC signal, and a high amount of energy from disturbances is expected outside the frequency content of DC signal, resulting in electric cars [42], cruise ships [43], and others may be interesting environments for WEH as well.

B. Frequency Band

Another way to classify EH in electric power systems is in terms of the frequency band. This classification contemplates EEH, MEH, and WEH because they make use of circuitry that is responsible for performing EH, which is tuned with respect to the chosen frequency (or frequency band) of electric signals flowing through power lines. In this regard, well-established frequency bands in the PLC community are adopted to encompass the EH potential of distinct components of disturbances in power lines, see Table IV.

TABLE IV: The frequency bands from PLC systems.

Technology	**Frequency Band**	**Data Rate**
BB-PLC	1.7 MHz - 250 MHz	< 1 Gbps
NB-PLC	3 kHz - 500 kHz	> 500 kbps
UNB-PLC	30 Hz - 3 kHz	≤ 120 bps

Fig. 5 shows the frequency bands of PLC systems in comparison to a typical division of the radio spectrum. Note that the higher the occupied frequency bandwidth by a PLC technology, the greater the minimum frequency of it, and, as a consequence, few high-amplitude components of disturbances, which are mainly related to harmonics of the AC mains signal, are present in electric signals. However, a wide frequency bandwidth implies that a numerous variety of RF induced signals are encompassed and, therefore, the harvested energy from the disturbances in electric signals may be large in a wide frequency bandwidth. Grounded on these discussions, using distinct frequency bands for EH in power lines may present different advantages and drawbacks, thus four frequency bands can be proposed to easily highlight these features. The suggested frequency bands are the ones delimited by broadband-PLC (BB-PLC), narrowband-PLC (NB-PLC), and ultra-narrowband-PLC (UNB-PLC) technologies for WEH, while AC mains frequency is adopted for both EEH and MEH. This classification is described and discussed in an EH perspective as follows.

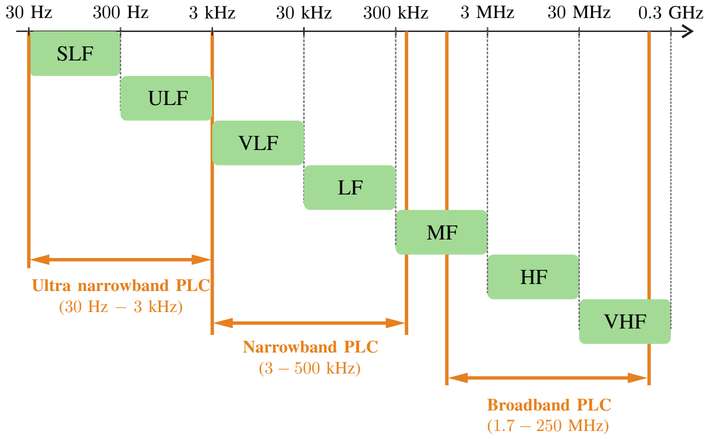


Fig. 5: Frequency bands for PLC systems and the radio spectrum.

1) BB-PLC spectrum: The BB-PLC system is designed to operate in the frequency band from 1.7 MHz up to 250 MHz with a data rate up to 1 Gbps [44]. Although the research activities focus on the aforementioned frequencies, the BB-PLC standards and technologies usually adopt a shorter frequency bandwidth. For instance, the BB-PLC technology is upper bounded by the frequency of 30 MHz by European Committee for Electrotechnical Standardization (*Comité Européen de Normalisation Électrotechnique* in French) (CENELEC) [45], 86 MHz in accord with the ITU-T G.hn and HomePlug AV2 standards [46], [47], and 100 MHz in the IEEE 1901 standard [48].

This frequency band covers some high-frequency PLC additive noise components, specifically a broadband spectral content of electric signals in this frequency band is due to RF signals induced in power lines (narrowband noise) from radio broadcasting stations, amateur citizen radios, broadcasting TV stations, and so on. Due to the wide frequency bandwidth of this spectrum range, it can be expected that a numerous variety of narrowband disturbances and impulsive noise components are present in it and, thus, the energy obtained from this frequency band is expected to be great [33]–[35]. BB-PLC systems could be designed to perform WEH from AM signals ($0.5-1.7$ MHz in America), FM signals ($88-108$ MHz) [36], and TV signals (54-216 MHz). If the dedicated EH approach is considered, the BB-PLC signal that traveled through the power line channel is received by an EH device, and therefore, it can be seen as a source of energy as well. In this regard, optimum power allocation techniques could be used to improve the energy harvesting process by an EH device due to the frequency selectivity of BB-PLC channels. Also, if a BB-PLC system allocates the power in the lower frequencies of the spectrum, which impose the lower attenuations in a BB-PLC signal, then more energy would be harvested by the EH device.

2) NB-PLC spectrum: The NB-PLC system comprises the technologies that operate in the frequency band from 3 kHz up to 500 kHz. NB-PLC systems can be categorized as low-data-rate or high-data-rate ones. The former is related to a single-carrier scheme that achieves data rates of a few kilobits per second, while the latter is associated with multi-carrier systems capable of achieving data rates over 500 kbps [44]. Furthermore, distinct frequency bands are used around the world, for instance, Europe standardized the use of NB-PLC in the CENELEC band ($3-148.5$ kHz) [45], the US standardized the Federal Communications Commission (FCC) band ($10-490$ kHz) [49], Japan adopted the Association of Radio Industries and Businesses (ARIB) band ($10-450$ kHz), while China adopted the Chinese band ($3-500$ kHz).

Most of the supraharmonics components are concentrated in the lower frequencies related to the NB-PLC systems. Except for the narrowband and high-frequency colored background noises, the WEH in the NB-PLC frequency band can harvest energy from several components of the PLC additive noise. In fact, the spectral content of the disturbances in electric signals in the frequency band related to NB-PLC systems has an interesting EH potential, especially due to the colored background noise that presents a high power below 500 kHz. Furthermore and similar to BB-PLC systems, WEH can be designed to encompass the frequencies from 500 kHz to 1.7 MHz, which is the frequency band gap between BB-PLC and NB-PLC technologies because it allows harvesting the energy from AM signals (narrowband noise) induced into power lines [32]. If a dedicated EH approach is used, then an EH device can also take advantage of the frequency selectivity of the NB-PLC channel to optimize power transmission. In other words, a NB-PLC transmitter device can allocate the power to the subchannels that present the lowest attenuations and, thus, the received signal by the EH device would have a larger amount of energy.

3) UNB-PLC spectrum: The UNB-PLC system operates in the upper part of the super-low frequency (30-300 Hz) band or in the ultra-low frequency (0.3-3 kHz) band and offers data rates up to 120 bps [50]. Most of UNB-PLC systems transmit the data during zero crossings of the AC mains voltage signal because it avoids being affected by the high amplitude of AC mains signal. It is important to mention that no standards were developed for UNB-PLC technology, and their commercial solutions are proprietary.

This frequency band covers the spectrum content from the 2nd up to the 60th or 50th harmonic component of the voltage signal, interharmonics, and the lower part of the supraharmonics[2]. Note that this frequency band presents the lowest frequency bandwidth compared to the ones used by any other PLC system. Also, it is appealing for WEH because the frequency proximity between harmonic components and AC mains frequency may result in a high amount of harvested energy to the EH device [2], [37]. Regarding the use of WEH, some low-frequency PLC additive noise components can be harvested in this frequency band, such as the low-frequency colored background, periodic and non-periodic impulsive ones [40], [51]–[53]. As previously mentioned, most of the UNB-PLC systems perform data communication around zero crossings of the AC mains voltage signal and, therefore, the presence of UNB-PLC signals and disturbances due to the loads' dynamics is periodic and does not occur simultaneously over time. The data communication results in energy at the

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[2] Supraharmonics are the disturbances in electric signals with frequencies between 2 kHz and 150 kHz.

EH device that comes from the UNB-PLC signal that traveled through power lines while the disturbances in electric signals generate the energy contained in the UNB-PLC additive noise. If a dedicated EH approach is adopted, then the EH device can take advantage of this non-simultaneous occurrence between the data communication and disturbances in electric signals to harvest a constant amount of energy over time.

4) AC mains frequency: The AC mains frequency is 50 or 60 Hz depending on the country and its purpose of delivering energy to loads. As a matter of fact, the energy associated with it is the highest one in comparison to any other spectral components. Therefore, both E-field and M-field associated with the AC mains signal are strong in the vicinity of a power line. Naturally, the EEH and MEH were designed to harvest the energy generated by, respectively, the E-field [14]–[23] and M-field [24]–[31] of the AC mains signal.

IV. HARVESTING METHODS AND CIRCUITRY

Unlike the usual loads that are connected to the electric power systems, the EH-based supplying devices count with the energy obtained from an artificial or natural source, in which the former can be harvested at any time while the latter may be intermittent over time. Thus, the management of energy use and energy storage must be established by a proper harvesting method. To carry out the energy harvesting process, an EH device can make use of three typical harvesting methods: *harvest-use*, *harvest-store-use*, and *harvest-use-store*, which are briefly outlined as follows [5], [54]:

- *Harvest-use*: The harvested energy is immediately used to supply the EH device. In other words, there is no buffer to store the harvested energy for future use, and the normal operation of the EH device over time requires that the harvested energy constantly exceed the minimum demand. Otherwise, this device will not be able to operate, and it will stay in sleep mode or turned off.
- *Harvest-store-use*: The harvested energy is initially stored in the buffer (energy storage element), and then it supplies a given device. If the harvested energy surpasses the EH device's energy consumption at any time, then the energy excess is stored in the buffer for future use. A drawback is that the self-discharging feature of the energy storage element can negatively affect the stored energy.
- *Harvest-use-store*: This method counts with two energy storage elements. The harvested energy is temporarily stored in one energy storage element and can be used immediately on demand by the EH device, while the remaining energy is transferred to another energy storage element for later use. Note that this method is the most complex one due to energy management and can result in high relative energy losses.

In the era of the IoT, many low-power consumption devices that intermittently exchange data are connected to data networks, and consequently, they can perform scheduled or unscheduled data communication over time. Note that the unscheduled data communication can occur over user demand or anytime that an EH device has obtained energy that exceeds the minimum energy demand to perform data communication. If scheduled data communication is used, then the preferable harvesting methods are the harvest-store-use and harvest-use-store ones because they guarantee the necessary energy whenever data communication needs to be performed. However, an EH device that uses unscheduled data communication can adopt any harvesting method. It is important to emphasize that this discussion also depends on the predictability of the chosen source of energy for performing EH. For instance, if WEH is used, then the dynamics of harvested energies associated with wasted powers during the weekdays present a cyclostationary behavior as is emphasized in [37], and, as a consequence, the energy harvested by the EH device can be predicted, such that the harvest-use method could be used at any time the harvested energy is greater than an energy threshold, which is used to start the data communication by an EH device.

Based on the fact that the main application of EH is to feed low-power consumption devices that are capable of intermittently transmitting data in low-bit-rate sensor networks, which can be based on wireless or wireline media (e.g., air and power lines), the combined use of EH and data communication is a powerful approach to come up with effective and efficient low-bit-rate sensor networks. When data communication and EH occur in the same frequency band, it is called *in-band* strategy, while the data communication and EH occurrence in distinct frequency bands is named *out-of-band* strategy. The former benefits from less complex circuitry, which is used for both EH and data communication, while the latter is more complex because the circuitry for EH and data communication are independent of each other. Despite the energy availability of a specific energy source, the full potential of EH can only be achieved if the circuitry responsible for harvesting the energy offers high efficiency. In other words, this circuitry needs to optimally take advantage of the input power in the EH device by using low-power loss components in the circuitry. In this regard, Fig. 6 shows the block diagram of a typical EH device circuitry, where its main parts are represented by blocks that offer individual efficiency factors, which are detailed in [54], [55].

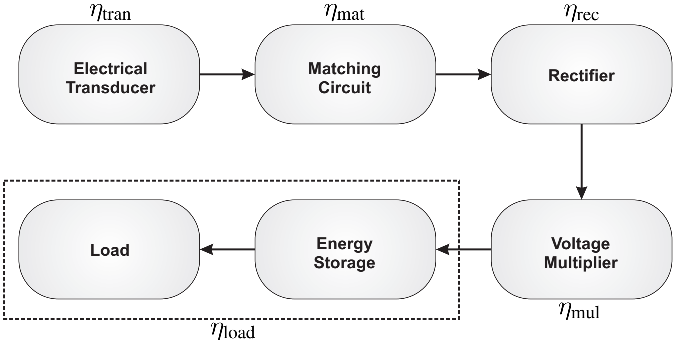

Fig. 6: Block diagram of an EH device circuitry.

The overall efficiency factor[3], $\eta \in \mathbb{R}_+, 1 \geq \eta > 0$, of the EH device circuitry is given by [55]

$$\eta = \frac{\text{Output power}}{\text{Input power}}, \tag{1}$$

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[3] Usually, the efficiency factor is called RF-to-DC efficiency (or conversion) factor in wireless EH [54].

in which the output power is the power delivered to the load and the input power is the received power at the input of the EH device. Note that the input power originated from AC voltage and current signals, while the output power is associated with DC voltage and current signals. The circuitry that turns the input power into the output power counts with the electrical transducer, matching circuit, rectifier, voltage multiplier, and energy storage. Note that the load can represent a data communication module, among others.

Electrical transducer (η_{tran}): The electrical transducer is the part of the EH circuitry that converts an input power associated with the time-varying E-field or M-field, radiated from the power line, into an AC voltage signal. Note that EEH and MEH are accomplished by using capacitors and inductors, respectively, while WEH can be implemented by using the usual PLC coupling circuit, which is inductive or capacitive [41], tuned in the frequency band of interest.

Matching circuit (η_{mat}): The matching circuit is responsible for performing the impedance matching and, as a consequence, maximizing the power transfer between the electrical transducer and the rectifier. It is a resonator circuit usually composed of reactive components, such as capacitors and inductors, operating at the desired frequency band, in which the efficiency of the impedance matching is optimized. It is noteworthy to mention that this part of the EH circuitry is complex since the dynamics of access impedances in electric power systems is a challenging problem to deal with [56].

Rectifier (η_{rec}): The general purpose of a rectifier is to make the conversion of AC voltage signals into DC voltage ones. It is usually composed of diodes and capacitors. The most common circuits in the literature are half-wave, full-wave, and bridge rectification. Also, the Schottky diodes are preferred in the rectifier circuits due to their low forward-voltage drop, low power consumption, low parasitic effects, and high switching speed [55].

Voltage multiplier (η_{mul}): The voltage multiplier is used to increase the output DC voltage level of the rectifier, which may not be sufficient to drive a device or to store in a battery. As it is composed of capacitors and diodes, high-efficiency factors can be achieved in the voltage multiplier by using diodes with a low forward-voltage drop (i.e., Schottky diodes). The capacitor ensures the smooth delivery of power to the load or energy storage element, and it can also serve as a short-duration energy reserve when energy is unavailable at the input of the EH device.

Energy storage or load (η_{load}): The last part of the EH circuitry is responsible for storing or consuming the output power. If the *harvest-use* method is used, then the load will be directly connected to the voltage multiplier, and, as a consequence, the efficiency factor depends upon the impedance matching between the load and voltage multiplier circuit. However, if either *harvest-store-use* or *harvest-use-store* methods are applied, then the energy storage takes place before its consumption. In this case, the efficiency factor is also affected by the self-discharging feature of the energy storage element. The energy can be stored by batteries, supercapacitors, or a combination of them [55].

In the way it was described, the overall efficiency factor can be modeled by

$$\eta = \eta_{\text{tran}}\eta_{\text{mat}}\eta_{\text{rec}}\eta_{\text{mul}}\eta_{\text{load}}. \tag{2}$$

As a numerical example, the overall efficiency factor for wireless EH devices can vary from 0.15 up to 0.83 [55]. Notice that it depends on many parameters such as the input power, the operational center frequency, the frequency bandwidth, and the load impedance, among others. Generally, the higher the input power, the higher the overall efficiency. For low input power levels, the overall efficiency factor can even drop to zero because the diodes' forward-voltage drop of both rectifier and voltage multiplier circuits can be higher than the AC voltage signal at the output of the electrical transducer.

V. CASE STUDY: EVALUATION OF ENERGY HARVESTING

Based on [37], this section shows the quantitative evaluation of WEH in terms of wasted power and the number of transceivers of IoT devices that the wasted energy could power. The wasted power (i.e., the wasted energy dynamic) is defined as the power that could be harvested from the harmonic components of electric signals by assuming an ideal overall efficiency factor ($\eta = 1$). The analysis hereby presented results from a measurement campaign of voltage and current signals, which was held in a Brazilian LV electric power system of a post-graduate building.

In this context, Fig. 7 shows the wasted power of harmonics as a function of the daytime, on weekdays (top) and weekends (bottom), for two different weeks, and also the average wasted power. Each day is represented by time indexes of $\{0, 6, 12, 18\}$ hours, starting on Monday (weekdays) and Saturday (weekend). The authors of [37] showed that the wasted power on weekdays is a cyclostationary random process with values ranging from ~ 0 to approximately 14.5 W. Also, the highest values occur around lunchtime, the lowest at midnight, and the average is 4.3 W. On the other hand, on weekends, the wasted power ranges from ~ 0 to 2.2 W with stationary random behavior, which results in 0.8 W of average power.

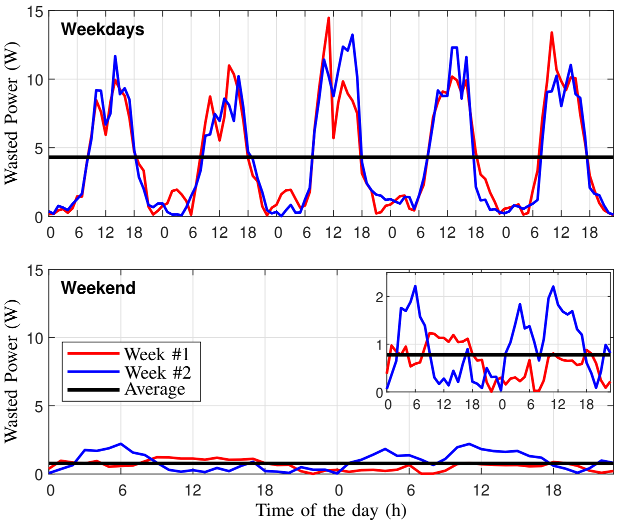

Fig. 7: Wasted power for distinct days of the week.

Moreover, on weekdays, the wasted power presents a bell-shaped form, with the higher values occurring near midday and the lower ones at midnight. Also, around the peaks of the wasted power (i.e., lunchtime), a variation is observed because students and staff leave the building and, as a consequence, the energy consumption associated with air conditioning, computers, and other types of electronic equipment decreases. It means that the wasted energy associated with the undesirable components of electric signals increases when the energy consumption is high, and consequently, the possibility of harvesting more energy also increases.

Now, the usefulness of WEH by comparing national and global perspectives is briefly discussed. In this context, Fig. 8 shows coarse estimates of the number of transceivers of IoT devices that the wasted energy could power in some usual electricity sectors in Brazil and worldwide, considering $\eta = 0.5$, the time between two consecutive messages equals to 1 minute, and five usual data communication protocols: ZigBee, Bluetooth, Sigfox, LoRa, and NB-IoT.

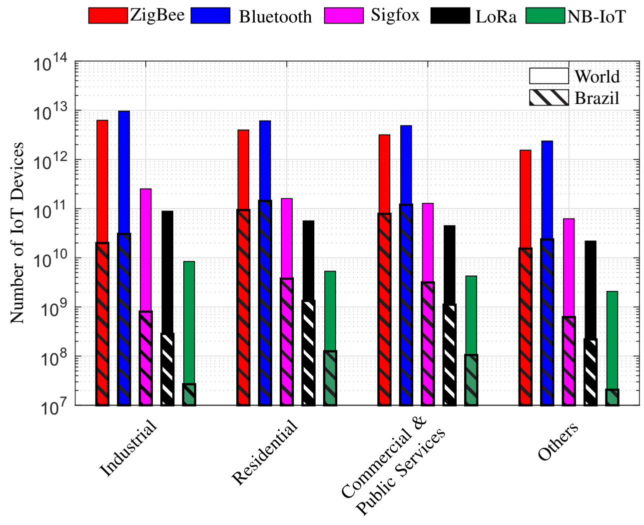

Fig. 8: A coarse estimate of IoT devices that could be powered with the wasted energy in Brazil and worldwide in 2019.

We can see that the Industrial and Residential sectors have the highest potential for harvesting the wasted energy from a worldwide perspective and, consequently, feeding the transceivers of IoT devices. On the other hand, in Brazil, the highest number of transceivers of IoT devices are in the Residential, Commercial & Public Services. Also, it is possible to see that the number of IoT devices that could take advantage of the wasted energy in each sector is in the order of trillions worldwide, while these values are in the order of dozens of billions for Brazil.

When the overall Brazilian and global scenarios (i.e., the sum of the contribution of all sectors) are considered, the number of IoT devices powered by harvesting the wasted energy associated with electric signals in electric power systems are detailed in Table V. We can see plenty of wasted energy, which is sufficient for annually feeding from 20.05 billion to 22.944 trillion of IoT devices' transceivers that run NB-IoT or Bluetooth protocols worldwide, respectively. For Brazil and the same protocols, these values range from 280 million to 317.92 billion. In general and for all sectors, Brazil sums up to 1.39 % of the World's wasted energy and, consequently, the capacity of feeding the transceivers of IoT devices as well.

TABLE V: Estimated number of IoT devices' transceivers powered by harvesting the wasted energy in electric power systems (billions).

Data Communication Protocols	Brazil	World
Zigbee	207.06	14,944
Bluetooth	317.92	22,944
LoRa	8.35	602.39
Sigfox	2.94	211.94
NB-IoT	0.28	20.05

This analysis, together with results presented in other aforementioned works, supports the statement that WEH can bring many benefits not only related to electric power systems but also to low-power consumption devices and the environment as well. As highlighted by [2], [37], WEH in electric power systems can reduce the THD, increase the energy efficiency of electric power systems, and help to reduce the emission of carbon becoming a green solution for future systems.

VI. FUTURE TRENDS

Building upon the insights garnered from earlier discussions on EH within electric power systems, we can delineate several pivotal directions that will shape the future trajectory of this technology. The ensuing subsections delve into critical facets of EH, emphasizing the integration with emerging technologies. These discussions aim to chart a course for advancing EH in electric power systems, addressing technical challenges, and exploring innovative applications in the realm of electric power systems. Through a comprehensive examination of these aspects, we aim to underscore the potential of EH to revolutionize energy sustainability and efficiency in the face of evolving energy demands and technological landscapes, mainly for data communication purposes.

A. Harvesting Circuitry

EH within electric power systems represents a compelling avenue for research geared towards developing more sustainable solutions. The advent of renewable energy sources, such as wind and solar, has introduced increased variability and disturbances into the electrical grid. This variability underscores the growing appeal of EH technologies, particularly in the context of mitigating technical losses that become more pronounced in large-scale power generation facilities. However, the field is currently confronted with a significant challenge: the absence of specialized circuits capable of performing EH across the diverse conditions present in electric power systems, including variations in voltage levels, conductor configurations, and environmental factors.

In this sense, a critical area for research and development lies in the design of EH circuits that can maintain a positive energy balance, thereby enabling the efficient extraction of energy from harmonics and other components from electric signals. The dynamic nature of access impedance in electric power systems, characterized by its time- and frequency-dependent fluctuations, poses a considerable hurdle for the practical deployment of EH technologies. Achieving optimal circuit matching under these conditions enhances energy conversion efficiency.

Further investigation is essential to delineate the specific contexts in which EH can be effectively implemented, along with the potential benefits it could afford to various stakeholders, including consumers, prosumers, and electric utilities. Additionally, there is a pressing need to advance research into refining rectification and energy storage methodologies. Such advancements are critical for boosting overall system efficiency and ensuring that EH initiatives result in a net positive energy balance. This endeavor not only holds promise for enhancing the sustainability of electric power systems but also for paving the way towards a greener and more resilient energy infrastructure.

B. Hybrid Communication Possibilities

Recently, the necessity of advances in data communication has pushed forward the development of hybrid data communication systems [57]–[60]. Although an improvement in data communication through the individual use of a power line or wireless medium can be attained with cooperative protocols [61]–[64], the exploitation of the existing diversity between both media [65] can offer remarkable benefits to the low-bit-rate applications (e.g., flexibility and reliability). As a signal carrying information can be seen as a source of energy as well, many possibilities of using EH emerge when hybrid data communication systems are implemented. In the following, it is described the two possible configurations for hybrid systems based on the combination of PLC and WLC.

- *Hybrid PLC/WLC system*: In this case, both data communication media are used simultaneously to increase the reliability or the data rate compared to non-hybrid data communications. Here, the hybrid PLC/WLC device uses distinct frequency bands in PLC and WLC, and relay devices are usually associated with this configuration. This configuration is illustrated in Fig. 9 and the literature about can be seen in [58], [59], [66]–[73].

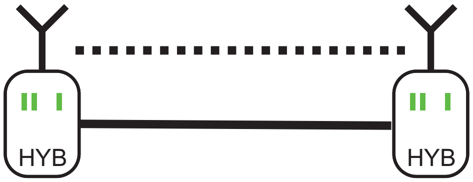

Fig. 9: Parallel configuration (hybrid PLC/WLC system).

As the hybrid PLC/WLC device is capable of communicating through two different media, it can harvest energy from four distinct sources in a dedicated EH approach: i) PLC FoN received signal; ii) PLC additive noise; iii) WLC FoN received signal and; iv) WLC additive noise. On the other hand, an ambient EH approach includes only additive noises from power lines and wireless media. In this sense, this configuration may guarantee an effective energy transference between data communication devices. It is important to highlight that, in this case, a hybrid PLC/WLC device can simultaneously perform data communication in one medium while making EH in another one, resulting in a continuous activity of this device [74].

- *Hybrid PLC-WLC system*: In this configuration, the signal transmitted by a device in one communication medium is radiated and sensed by another one that is designed to operate in the other communication medium but in the same frequency band. This configuration is shown in Fig. 10 and the literature on this can be seen in [36], [44], [75]–[78].

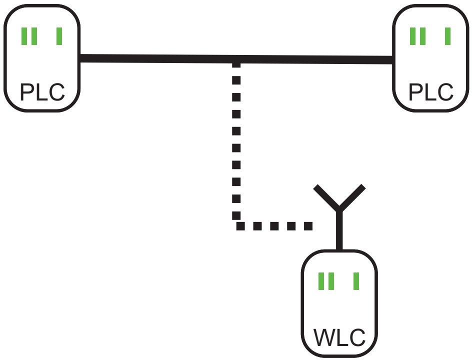

Fig. 10: Concatenated configuration (hybrid PLC-WLC system).

Assuming a dedicated EH approach and the PLC→WLC direction, the EH can occur at the receiver device in both WLC FoN received signal and additive noise. On the other hand, the receiver device of the WLC→PLC direction can take advantage of both the PLC FoN received signal and additive noise (see [79], [80] for more details). Interestingly, the data communication device that was not intended to directly participate in the data communication can also take advantage of it. For instance, the left PLC device in Fig. 10 is communicating with the WLC device. However, the right PLC device is capable of energizing itself by means of both PLC FoN received signal and additive noise due to the broadcasting nature of power lines.

If a relaying EH device is considered, either one of the *in-band* or *out-of-band* strategies can be used in tandem with any of the aforementioned configurations. As a matter of fact, the use of a relay is necessary for the adoption of any strategy because both strategies depend on the device performing both EH and data communication in a single medium, which is not the case for any EH device in the previously presented configurations. For instance, the concatenated configuration could consist of a WLC (EH) receiver device that harvests its energy from the electromagnetic wave radiated from the electromagnetically unshielded power line (baseband) and, then, it could carry out data communication to another WLC (EH) device in one of the ISM frequency bands. On the one hand, the *in-band* strategy consists of a single circuitry for both EH and data communication. Thus, the commutation between these two purposes is necessary. In this case, the EH device depends upon using an energy storage element, and the data communication only reaches a reduced data rate. On the other hand, if the *out-of-band* strategy is adopted, then independent circuits for EH and data communication are used, and the use of an energy storage element is not required. Therefore, the data communication could be continuous, and a higher data rate is expected compared to the previous strategy.

C. Optimal Power Allocation

In electric power systems, energy transmission occurs in a single frequency, not for arbitrary reasons. Indeed, one can demonstrate that the maximum power transfer is accomplished as the total power is allocated only to a unique frequency that provides the maximum efficiency in the considered medium [81]. As for data communication optimization (i.e., to maximize the mutual information), the information theory states that the available power should be allocated according to the water-filling technique not to a single frequency but to a reasonable bandwidth [82]. In this sense, there is a clear trade-off between information and power transfer [81], which can be adjusted by power allocation techniques and must be investigated.

Since the ambient EH approach considers additive noise and not the transmission power, this approach will not be assumed when jointly exploiting information and power transfer. On the other hand, the dedicated EH approach may be investigated, focusing on the FoN received signal. For instance, power allocation and the dedicated EH approach may be extremely useful in case of power outages. A central node with sufficient battery may perform power allocation to provide both information and energy to multiple nodes/users within a communication network, keeping it operational. In this context, however, several aspects that influence EH and power allocation must be taken into account within the electric power system scenario, such as fairness among users [83], storage capacity [84], causality constraints on channel conditions and energy harvested [84], [85], optimal save-ratio strategy [86], and others [83], [87], [88].

At last, a joint investigation of hybrid systems and power allocation can also be considered a promising direction to improve the dedicated EH in electric power systems. In [73], [89], the authors aimed to optimize the data communication of a hybrid PLC/WLC system under different power constraints. They demonstrated that only one medium (i.e., power line or wireless) should be used in a given frequency band to optimize the available resources. In other words, if the primal objective is to optimize data communication, then the employment of both power line and wireless media for data communication purposes in the same frequency band characterizes a waste of power, depending on the considered type of hybrid PLC/WLC system. In this sense, the medium that is not considered for data communication in a hybrid PLC/WLC system can be used from another perspective, including EH. Moreover, the investigation of other types of hybrid systems based on PLC and WLC in which power allocation techniques can be exploited for the benefit of data communication and EH is open and may be explored. Therefore, these topics may drive research on power allocation and EH soon.

D. Physical Layer Security

As aforementioned, the use of EH devices in PLC networks has the potential to reduce the wasted energy in electric power systems since they can capture part of the mains energy radiated in the form of E-field and/or M-field for data communication purposes. Nonetheless, EH devices typically have limited hardware resources, making them unsuitable for embedding traditional encryption mechanisms [90]. This constitutes a serious security breach since it makes sensitive information from the PLC network easily accessible to eavesdroppers. In this regard, an interesting solution to contour this problem could be using Physical Layer Security (PLS) schemes.

The PLS uses the knowledge of the communication medium to provide information security in a data communication link using limited computational resources [91]. Roughly speaking, the PLS relies on two approaches. The first one aims at degrading the eavesdropper's Signal-to-Noise Ratio (SNR) about the legitimate receiver. The second one uses the random characteristics of the communication channel to generate keys and then provide secrecy. In the literature, a few studies investigated the deployment of PLS schemes in PLC systems. Most of them considered the keyless approach [92]–[96] whereas only [97] studied the second approach. Furthermore, most of the studies related to the first approach quantified PLS in a single-user scenario in terms of achievable secrecy rate. Also, in these investigations, the authors assumed a complete knowledge of the eavesdropper's channel state information, except in [96], [97].

Finally, to the best of the authors' knowledge, there is no study in the literature that investigated the application of PLS in PLC systems composed of EH devices. Note that, in this scenario, traditional approaches, such as maximizing secrecy achievable data rate or minimizing secrecy outage probability, could be replaced by the optimization of the secrecy energy efficiency metric discussed in [90], [98]. This metric is a trade-off between the secrecy rate of the communication link and energy used by the EH devices [90]. Also, PLS metrics could be used as constraints in an optimization problem related to an EH network [90]. In summary, the study of PLS in PLC systems is still in its infancy and the topics presented in this discussion may point out some future research directions.

E. Negawatts Market

Recently, the concept of negawatts was put in evidence [99]. Negawatt was introduced in 1985 [100] as an energy management technique, such that negawatt-hour is the unit of energy saved as a direct result of energy conservation measures. As stated by the author, it is much cheaper to save electricity than to make it. For example, the change of the lighting system of an entire country for the most efficient one could save up a huge amount of watts and, consequently, send back this power – or negawatts – to the power plant or another consumer. Thus, it meets the EH concept in electric power grids, which cope with the UNB-PLC spectrum's energy potential [37].

As highlighted in Section IV, the harvesting circuitry depends on the efficiency of distinct parts of the EH device.

High-efficiency circuits and their spread in electric power grids may allow the creation of the negawatt market, which can be considered a secondary market where electricity is allocated from areas of less use to areas of greater use [101]. This would be a secondary market, because it would reallocate electricity from one consumer to another within the already existing energy market. Negawatt market and pervasiveness of smart grids (SGs), including distributed generation and the correct energy management, could significantly benefit the entire market, especially the utility consumer. In general, this proposal would bring the following benefits: energy cost reduction for consumers who trade their demand in periods of high prices for periods of lower prices; reduction in the overall cost of generating the system because changes in consumer behavior will eventually flatten the overall demand profile; cost reduction translates to lower prices to avoid price peaks (i.e., very large price increases in short periods of time); reduction in the ability of generating companies to exercise market power.

F. Non-Orthogonal Multiple Access

NOMA is a useful method to improve the spectral efficiency of wireless communication systems [102]. NOMA transmitters adopt superposition to stack the wireless signals aiming to achieve multiple receivers. Successive interference cancellation (SIC) is carried out at each receiver node to extract the signals addressed to them and cancel those intended for other ones. NOMA can connect multiple receiver nodes by using time-frequency resources and its association with EH is currently being considered for future wireless networks [103].

NOMA transmitters allocate low power to the signal addressed to closer receivers, while the opposite occurs for distant receivers. After extracting the signal of interest, the receiver node discards any other superposed signals. From an EH perspective, the power contained in every non-interest signal can be harvested instead of discarded. In EH-based SIC, the furthest receiver first extracts its signal and then harvests the power of the remaining ones, while the nearest receiver cancels non-interest signals before extracting the one addressed to it. Thus, the furthest receivers can take more advantage of the received power than the nearest ones.

NOMA with WEH could be similarly implemented in PLC modems. More specifically, NOMA in BB-PLC or NB-PLC follows the same principles as its wireless counterpart, in which the signal attenuation with distance in power lines is used to establish a NOMA-based communication [104]. The PLC receiver that performs WEH can benefit from non-interest signals in SIC, characterizing an *in-band* strategy. In this case, closer receivers would have a great signal (of interest) strength due to less attenuation with distance, while the distant ones would have great harvested power - creating a balance between received signal strength and harvested power among distinct PLC receivers. As an alternative, BB-PLC and NB-PLC systems could simultaneously implement both *in-band* and *out-of-band* strategies, in which the latter would be carried on the UNB-PLC spectrum aiming the high amount of energy present in harmonic components.

VII. CONCLUSION

Aiming to contribute to advancing EH technologies and paving the way for their greater efficacy and integration into future electric power systems, this paper has offered an in-depth exploration of EH within the realm of electric power systems. It has systematically categorized EH techniques based on the voltage levels of the AC mains and the frequency bands utilized by electric signals. Moreover, it has elaborated on various EH methodologies, highlighting the efficiency gains achievable through the optimization of EH device circuit components. Conclusively, the study has projected into the future of EH, delineating emerging trends and innovations. These include the development of advanced harvesting circuitries, the integration of hybrid PLC WLC systems for EH, strategies for optimal power distribution, advancements in physical layer security measures, the exploitation of negawatts, and the application of NOMA techniques.

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