Review on Basic Solutions for Far-Field Wireless Power Transfer

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***Abstract*— Wireless power transfer (WPT) in the far-field offers significant advantages, including convenience and the ability to power multiple devices simultaneously. However, challenges such as efficiency, safety, and cost remain. Key applications include powering IoT devices, wearable electronics, and medical implants. Ongoing research aims to enhance performance and expand practical uses. Here we present a short review on basic principle and solutions for far-field WPT.**

Keywords—Far-field, wireless power transfer, antenna, sensor, IoT device

I. Introduction

For an extended period, electrical power transmission has predominantly relied on conductive wiring systems. This conventional approach presents several challenges, including degradation of materials due to wear and tear, an escalating number of cables, and the accumulation of waste batteries and accumulators. Wireless Power Transfer (WPT) technology offers a transformative solution that has the potential to revolutionize the primary modalities of power delivery, particularly for compact devices such as computer peripherals and various sensors utilized in automation systems, including smart home technologies within the Internet of Things (IoT) ecosystem. WPT is defined as a method of transferring electrical energy from one location to another through vacuum or atmospheric mediums, thereby eliminating the need for traditional conductive cables. This technology not only addresses the limitations associated with wired systems but also enhances flexibility and scalability in power distribution, paving the way for innovative applications across diverse sectors. As research advances in this field, WPT could significantly alter the landscape of energy transmission, fostering greater efficiency and sustainability in modern technological infrastructures [1].

WPT technology has transitioned from a theoretical concept to an integral component of commercial products, particularly in the realm of smartphones and portable smart devices. According to the mechanism of operation, WPT systems can be divided into two types: near-field and far-field [2]. In the early 2010s, prominent mobile device manufacturers such as CASIO, BlackBerry, and Samsung began incorporating wireless charging capabilities into their modern smartphones and wearable devices. Currently, several standards for near-field WPT systems exist, among them are Qi, Ki, MagSafe, AirFuel Resonance [3, 4]. Last decades several leading companies – including Qualcomm, PowerCast, Energous, Ossia, and WiTricity – have developed advanced products that facilitate energy transmission with notable efficiency over distances extending up to several meters. Furthermore, experimental research has demonstrated the feasibility of transmitting power across distances of tens of meters, achieving an efficiency rate of at least 35 %. This advancement not only underscores the potential of wireless power transmission but also highlights its growing applicability in various sectors, paving the way for a future where energy delivery is more flexible and less reliant on traditional conductive systems [5–7]. WPT systems in the far-field are also actively developing and there are already standards for them, for example, AirFuel RF [8].

Far-field WPT systems utilize propagating electromagnetic waves as an energy carrier. The following discussion will focus primarily on solutions in microwave frequency band, but power transfer in optical domain as well as solar energy harvesting also belong to far-field WPT technology [9, 10, 11]. In this paper we present a short review on far-field WPT challenges such as efficiency loss over distance, regulatory limitations on transmission power, safety concerns regarding human exposure to electromagnetic fields (EMF), alignment issues for optimal energy transfer, and the need for advanced technology to minimize interference and maximize range. We also demonstrate some realizations of the transmitting and receiving paths that overcomes these factors and provide hinder widespread adoption and implementation of far-field WPT.

II. Main Part

Traditional block diagram of a far-filed WPT system is demonstrated in Fig. 1. It includes the power transmitting path and power receiving path. The power transmit path consists of a generator, an amplification unit, and a transmitting antenna [12]. The power receiving system consists of receiving antenna, rectifier, microcontroller unit (MCU), battery, and load [11, 13–15]. The operational principle of far-field WPT in accordance with Fig. 1 is rather simple.

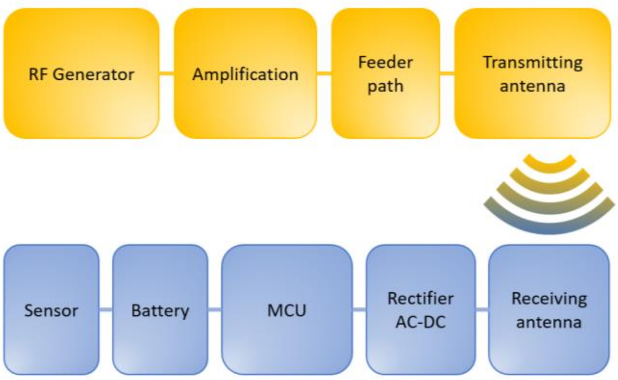

Fig. 1. Block diagram of a far-field WPT system

This work was supported by the Russian Science Foundation project No. 21-79-30038, https://rscf.ru/en/project/21-79-30038/

It operates by transmitting electromagnetic waves from a generator through an amplifier and feeding network to a transmitting antenna. The receiving antenna captures these waves, converting them into electrical energy via a rectifier. A MCU manages power delivery to charge a battery and supply a load. For the most efficient operation, the power transmitting and receiving paths must be within line of sight of each other.

Far-field WPT systems have increased safety requirements for the levels of surface power density, electric and magnetic fields, which are regulated by various standards [16, 17, 18]. From these standards the safe field levels and transmitter powers are 30 dBm, 41.8 dBm, and 45 dBm for the main operating bands – 915 MHz, 2400 MHz and 5800 MHz, respectively [8, 11]. The standards also regulate the equivalent isotropically radiated power of transmitters, to account for the increased field levels of high-gain transmitters. Thus, the equivalent isotropically radiated power levels of 36 dBm, 65.8 dBm, and 70 dBm for the operating bands – 915 MHz, 2400 MHz and 5800 MHz, respectively. As a result, from the maximum of isotropically radiated power we impose restrictions on the maximum gain of radiating antennas. This value can be defined as [8]:

$$EIRP = P - L + G_a, \quad (1)$$

where P – output power of the transmitter, L – fidder path losses , G_a – isotropic gain.

Thus, the equivalent isotropically radiated power levels for operating bands – 915 MHz, 2400 MHz and 5800 MHz, and are equal to 6 dB, 24 dB, and 25 dB, respectively [8, 19]. Such strict limitations are primarily due to the negative impact of elevated EMF levels on human health.

Therefore, there are several ways to ensure human safety for such systems:

- Active power control – includes automatic power reduction, both in the absence of charging devices and in the presence of a biological object, primarily a human being, in the path of the electromagnetic wave propagation [15].
- Using a lower transmission power to provide an unsafe zone in the vicinity of the transmitting system [8].

Usage of active power control allows to transmit higher power but requires additional feedback units [15, 20, 21], as well as embedded algorithms responsible for the detection of biological objects on the wave propagation path. Systems with lower power, on the other hand, are simpler to design and fabricate, but the transmitted power is also lower.

Using an active power control approach imposes limitations primarily on the power transmitting system. This is primarily due to propagation losses in free space, which increase as the operating frequency increases according to [8]:

$$L_{bf} = 20 \cdot \log_{10}\left(\frac{4\pi d}{\lambda}\right), \quad (2)$$

where d is the propagation distance, λ is the wavelength.

For example, the free space losses experienced by an electromagnetic wave at a distance of 1.5 meters, for the 915 MHz, 2400 MHz, and 5800 MHz operating bands, are calculated by (2), and are -35 dB, -43 dB, and -50 dB, respectively (Fig. 2). As can be seen, free-space losses grow rapidly with increasing frequency and are a major source of losses in WPT far-field systems. To compensate for high free-space losses, in far-field WPT systems with active power control, highly directional antennas are used. Normally the gain should be of at least 9 dB. Such transmitters could be realized as steerable antenna arrays, which also can control the direction of the main lobe [22].

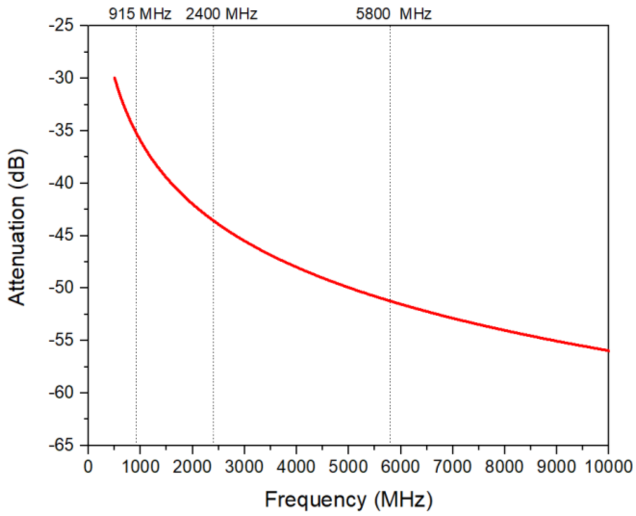

Fig. 2. Frequency dependence of free-space losses calculated for an electromagnetic wave propagating at 1.5 m

In 2015 a solution capable to transmit power over a distance of 55 meters with an efficiency of 42 % have been demonstrated [23]. For this purpose, four phased antenna arrays with an operating frequency of 5800 MHz have been utilized (Fig. 3 (a)). The total size of antenna array was 1.2 × 1.2 m^2, and total weight was 64 kg. The transmitted power of 1.8 kW was tested. The main limitation of the solution is poorly applicable in residential areas, due to the high level of radiation. However, such a solution can be used in outdoor areas, in particular for wireless charging of various drones, as demonstrated by the same research team in 2019 [24, 25]. In addition, the high weight and large geometric dimensions of the transmitter make it poorly applicable in IoT systems. Therefore, there is a need for miniaturization of active antenna arrays.

Energous Corp. proposes to use antenna elements with ceramic resonators [26, 27] in antenna arrays to reduce the mass and dimensional parameters (Fig. 3 (b)). This approach allows to reduce the size of an individual elements and the entire antenna array, but at the same time increases the weight of the entire system.

As an alternative to antenna arrays, a hexagonal variation of the horn antenna Fig. 3 (c) can be used [28]. With a relatively small size of 4 × 4 × 4 cm^3, with respect to antenna arrays, and an operating frequency of 5.8 GHz, has a gain more than 12 dB, but unlike antenna arrays is not able to deflect the direction of the main lobe, and therefore is suitable for WPT only for stationary receivers.

Low power wireless charging of portable/mobile devices has a several limitations, primarily related to the receiving antennas used. There is only one constraint imposed on the radiating antennas, which is to provide a uniform field profile with an radiation pattern (RP) of 90 degrees or more [8]. This restriction is rational because it maximizes the coverage area of a single transmitter.

The limitations related to receiving antennas are caused by the problems of AC-DC conversion efficiency at low power levels [29, 30]. A simple solution may be to use high gain antennas, but the receiving system is not always optimally located relative to the transmitter. Because of this, it is preferable to use receiving antennas with a wide RP and a bandwidth sufficient to receive frequency shifted signals. It is also preferable to be able to receive a signal of any polarization for the same reason.

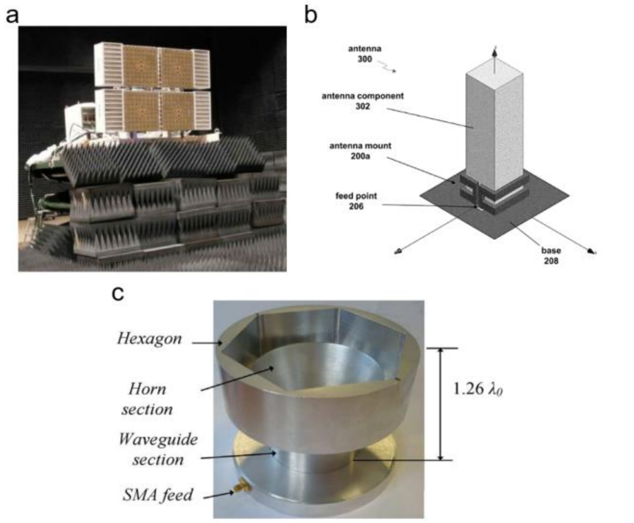

Fig. 3. Different variations of transmitting antennas in the far-field WPT systems (a) Transmitting antenna in antenna array design [23], (b) Antenna array element with ceramic resonator [26], (c) transmitting antenna in hexagonal horn design [28]

In [31], a combination of receiving antennas as well as power control circuitry on a single printed circuit board was demonstrated Fig. 4 (a). Such a solution at 915 MHz can be quite compact – 10 × 10 cm^2, but the use of dipole antennas as receiving elements is not an energetically optimal solution.

In [32] a working prototype was shown Fig. 4 (b), with a center frequency of 915 MHz, and representing a temperature sensor, with a condition-based triggering – when a certain temperature is reached, an acoustic signal is triggered. This solution is intended to be used in systems where the parameters are controlled by a human, for example, in greenhouses, which was demonstrated in this article. However, in the current design, this solution is poorly suited for use in complex automation systems with automatic temperature control, as the energy collected is not sufficient to power the control board.

An important factor for far-field WPT at low radiation levels is the presence or absence of a person in the vicinity of the device to be charged. Such devices can be both wearable electronics and various computer peripherals. The immediate proximity of a human affects the antenna alignment, and hence the efficiency of its operation. A solution may be to have multiple antenna elements, as shown in Fig. 4(c), some of which will be tuned to the operating frequency when operating in close proximity to a person [33], however, all antenna elements will be connected and hence some of them will not work. Therefore, active antenna tuning [33], which includes automatic switching between antenna elements, can be realized.

In addition to combining the antenna element with the power control circuitry, it is possible to combine it with structural elements of the receiving system. For example, the antenna element can be combined with a heat sink for electronic components (Fig. 4(d)) [34]. Such a solution allows to further reduce the cost of production and simplify the assembly of the receiving system.

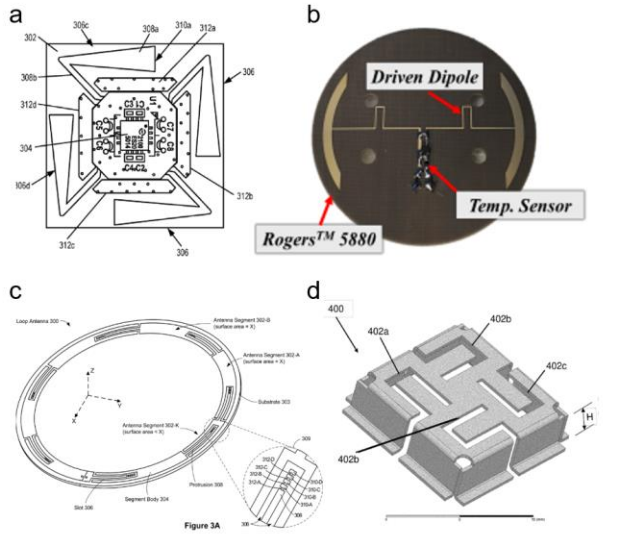

Fig. 4. The different variations of receiving antennas in the far-field WPT system (a) Receiving antenna combined with a power control board [31], (b) Prototype wireless temperature sensor [32], (c) Receiving antenna with automatic frequency tuning capability [33], (d) Receiving antenna combined with a heat dissipating radiator [34]

However, such solutions can reduce the efficiency of energy reception, and thus will be applicable only for energy transmission over short distances.

III. Conclusion

Here we presented a short review on basic principle and solutions of the far-field WPT systems in microwave frequency band. Several architectures for human safety from elevated electromagnetic adiation and several transmitter and receiver design concepts were discussed. Current research is aimed at finding a balance between transmitted/received power, mass and size parameters of the system. In the future, as the transmission distance increases and the efficiency of transmitted power improves, far-field WPT systems can be integrated into an increasing number of commercial products.

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