

Watt-level wireless power transmission to multiple compact receivers

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Abstract. This paper reports an electrodynamic wireless power transmission (EWPT) system using a low-frequency (300 Hz) magnetic field to transmit watt-scale power levels to multiple compact receivers. As compared to inductively or resonantly coupled coils, EWPT facilitates transmission to multiple non-interacting receivers with little restriction on their orientation. A single 3.0 cm³ receiver achieves 1.25 W power transmission with 8 % efficiency at a distance of 1 cm (350 mW/cm³ power density) from the transmitter. The same prototype achieves 9 mW at a distance of 9 cm. Moreover, we demonstrate simultaneous recharge of two wearable devices, using two receivers located in arbitrary positions and orientations.

1. Introduction

Over the past ten years, an alternative concept of recharging method for electronics devices, has gained interest: the wireless power transmission (WPT) [1,2]. The main advantage is to remove the burden of having to plug mobile electronic devices (laptops, smart phones, tablets, wearables) [3], to ease the recharge of electric vehicles [4], or to avoid surgical operations for battery replacement in biomedical implants [5]. Most of the research has focused on the electromagnetic coupling between two coils to wirelessly transfer power, namely inductive WPT [1,2]. In this approach, a transmitter coil produces a time-varying magnetic field that directly induces a voltage and current in a receiver coil (via Faraday induction) placed at a remote distance.

We have recently presented a different approach, named electrodynamic wireless power transmission (EWPT) [6–8]. This method relies on the use of a small permanent magnet in the receiver to achieve WPT. The transmitter produces a time-varying magnetic field, thereby inducing a magnetic torque/force on the magnet in the receiver. This coupling leads to the magnet motion, generating a voltage in the receiver windings, and if a load is connected, the EWPT is achieved. The system is operated at much lower frequencies (100–1000 Hz) than inductively or resonantly coupled systems (0.1–10 MHz) [1]. The lower frequencies facilitate higher safety margins for magnetic field amplitudes [9,10] and better penetration through electrically conductive media (metal, human body, seawater, ...). This enables wireless power delivery in a crowded environment, such as an office space, an automobile, or to a medical implant within the human body. Furthermore, unlike resonant-type WPT systems, there is little interference between receivers.

Various concepts of magnetic-to-mechanical-to-electrical wireless power transfer have been previously demonstrated, the earliest by magnetically exciting mechanical resonance in a receiver and then using either electrodynamic [6–8] or piezoelectric [11] transduction to convert this mechanical motion into electrical power. A system employing a cantilever-based oscillator yielded a power



transmission of 0.15 mW at 2.2 cm with 12 % efficiency [6]. A different prototype utilized a torsional resonator, achieving 3.1 mW at 1 cm (equivalent to a power density of 0.14 mW/cm^3), and 0.13 mW at 7 cm [7]. In these coil-based receivers, the inductive coupling between the transmitter coil and the receiver windings was shown to have a minor influence in the proposed EWPT mechanism [7]. An alternative design using a piezoelectric cantilever demonstrated a transmission efficiency up to 3 % [11].

A more recent variation on the EWPT concept was based on the continuous rotation of the permanent magnet rather than a resonant-based system. Under steady-state operation, the rotating magnet acted as a synchronous machine, supplying electrical power to an external load [8]. We demonstrated EWPT of up to 99 mW over a 5 cm distance at 0.5% efficiency (power density of 31 mW/cm^3) and 5 mW over 20 cm. This non-resonant approach enables power transmission over a range of frequencies, as opposed to only at the resonant frequency of the receiver.

This paper presents the recent improvements in the EWPT using the continuously rotating magnet system, eventually reaching a watt-level power transmission at close distance. The design of the transmitter coil has been modified in order to achieve a larger B-field at a lower input power. In parallel, the receiver architecture has been revised to enhance the flux change and increase the voltage output. These changes have enabled the implementation of DC rectifying electronics that can then lead to the recharge of wearable devices.

Section 2 first describes the working principle of EWPT using a continuously rotating magnet and it introduces the experimental setup used to perform EWPT along with the basic operation. Section 3 discusses the experimental results. Conclusions are provided in section 4.

2. Methods and Materials

2.1. EWPT Working Principle

The EWPT system reported here includes two major parts: a coil-based transmitter and a receiver system featuring a permanent magnet rotor that can continuously rotate within receiver windings, as illustrated in Figure 1.a. The transmitter coil is a pancake-shaped coil with 200 turns of 16 AWG copper wire, having an outer diameter of 15 cm, an inner diameter of 2.5 cm, and a length of 6 mm ($L=3 \text{ mH}$, $R=0.8 \Omega$) as illustrated by Figure 1.b. A low-carbon steel sheet (thickness=1 mm) is placed on the backside of the transmitter to enhance the magnetic flux lines on the transmitter frontside, therefore increasing the magnetic flux density in direction of the receiver. As presented in Figure 1.c, the receiver system comprises a diametrically magnetized, cylindrical, N42 grade Nd-Fe-B permanent magnet rotor (K&J Magnetics, D36DIA, diameter=4.8 mm, length=9.5 mm) that rotates on a ferrofluid bearing within a glass tube. The tube is inserted into a 3D-printed structure and wound with a single coil of 600 turns of 36 AWG copper wire. The final size is: width=17 mm, length=17 mm, height=11 mm, for a total active volume of 3 cm^3 .

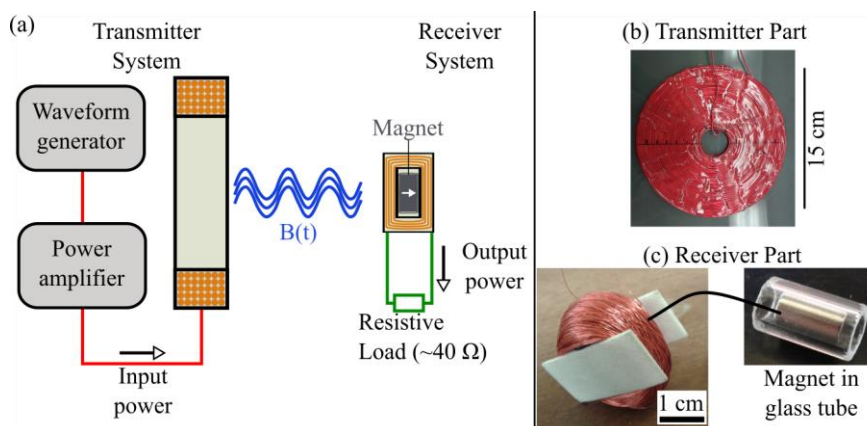


Figure 1: (a) Setup description of the electrodynamic wireless power transmission; (b) Picture of the coil-based transmitter; (c) Picture of the magnet in the glass tube that is part of the receiver.

To wirelessly transmit power, an AC current is injected into the transmitter coil, which results in the generation of a sinusoidal magnetic flux density $B(t)$. When the receiver system is placed nearby, the transmitted B-field magnetically couples with the receiver magnet, and forces synchronous rotation of the permanent magnet. The magnet motion produces a time-varying magnetic flux in the receiver windings, hence a voltage. If an electrical load is connected to the two terminals of the receiver windings, output power is delivered.

2.2. Experimental Setup

The EWPT system is characterized using the following setup. The initial input waveform is generated by a USB-powered Analog Discovery interface (Digilent Inc.) driven by a custom-made Matlab code. The signal is supplied, as an AC voltage, to a Crown XLS2500 linear power amplifier. The resulting output is an AC current input for the transmitter coil, monitored by a Tektronix TCP312A current probe connected to a Tektronix TCPA300 current probe amplifier. The transmitter voltage is measured with two 10x oscilloscope probes, each connected to one terminal. An Agilent DSO-X-2004A 4-channel oscilloscope is used to monitor the input current and voltage to the transmitter, and to subsequently calculate the input power. The output receiver voltage, measured across the receiver load, is measured with the Analog Discovery board, and the signal is later post-processed to extract the RMS voltage as a function of the transmitter frequency. The resistance of the receiver windings is independently measured with a Keithley 2000 multimeter, using the 4-wire configuration. The load resistance is matched to the coil resistance for optimal power transfer. For a given AC excitation of the transmitter (frequency, amplitude), the resultant B-field spatial distribution is measured with a Lakeshore XHMM-1482 axial Hall probe connected to a Lakeshore 475DSP gaussmeter.

2.3. Basic Operation

The frequency is swept from a low frequency, 40 Hz—where the receiver locks into synchronous, steady-state rotation—up to a point where the magnet stays rotating continuously (200–400 Hz). If the frequency is kept increasing, at a certain point, the magnet will lose synchronization with the transmitted B-field, resulting in no more magnet rotation. This upper frequency is called the maximal frequency and the output power at that frequency, the maximal output power. The frequency where synchronization is lost represents the “pull out torque” for a synchronous machine—the point where the magnetic torque acting on the magnet equals the sum of the opposing mechanical and magnetomotive torques [12].

3. Results and Discussion

First, the output power as a function of the transmitted B-field is characterized along the central axis of the transmitter coil. Next, the on- and off-axis wireless transmissions are measured. Last, successful recharge of commercial wearable devices is demonstrated.

3.1. Output Power vs B-Field

After placing the receiver system 1 cm away from the transmitter along its central axis, a sinusoidal current is injected in the transmitter coil. The resistive load is adjusted to $50\ \Omega$. The amplitude of the input current is varied from 0.6 A to 2.2 A, corresponding to an input power from 0.3 W to 15 W, respectively. It results in a variation of the B-field at the receiver location from $3.2\ \text{mT}_{\text{pk}}$ to $13\ \text{mT}_{\text{pk}}$. The resulting maximal output power is measured as a function of the transmitted B-field and the results are presented in Figure 2.a, showing a quadratic relationship, as previously reported [8]. A maximum output power of 1.25 W is achieved at $13\ \text{mT}_{\text{pk}}$. The transmission efficiency is extracted as the ratio of the maximal output power to the input power, and it is reported in Figure 2.b. It is found as $9.3 \pm 1.1\ \%$ for all tested B-fields.

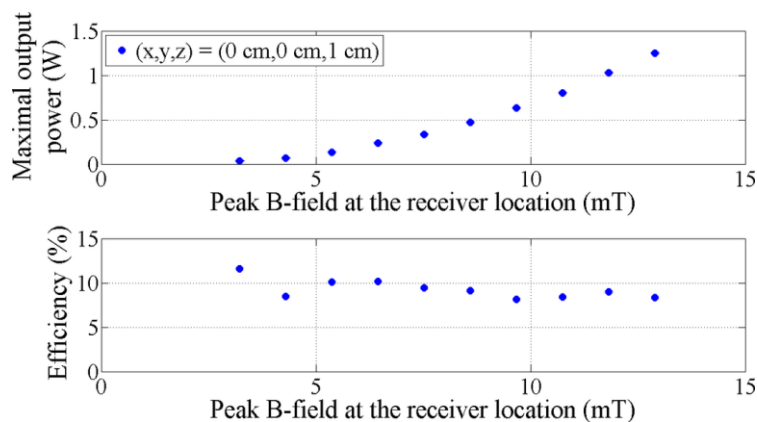


Figure 2: (a) Maximal output power and (b) transmission efficiency, as a function of the peak B-field at the receiver location.

3.2. On- and Off-Axis EWPT

For the subsequent experiments, the input current is fixed at 2.2 A (15 W). The distribution of the output power as a function of the on-axis position is performed and the results are presented in Figure 3. Each point represents the average value of three measurements, with the error bars too small to be noticed. Here, 1.25 W of power is wirelessly transmitted at 1 cm, while 9 mW is transmitted at 9 cm. This reduction in power is a consequence of the decay of the magnetic flux density with distance. A linear fit to the semilog function results in a slope of (-0.27).

The off-axis output power distribution is also measured, and the results are presented in Figure 4. The receiver is moved in one direction off axis, 1 cm above the transmitter, and the output power is extracted at each position. Each point represents the average value of three measurements, with the error bars too small to be noticed. At 7 cm off-axis (\sim transmitter radius), an output power transmission down to 8 mW is measured.

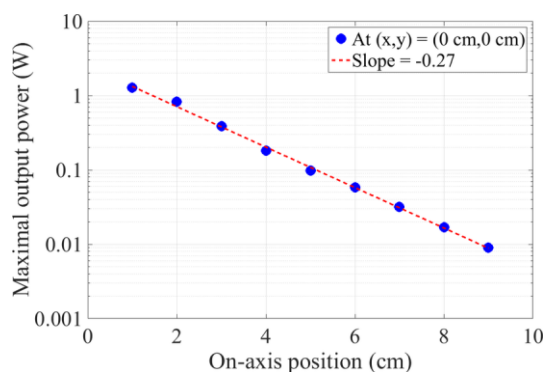


Figure 3: Maximal output power, as a function of the on-axis position.

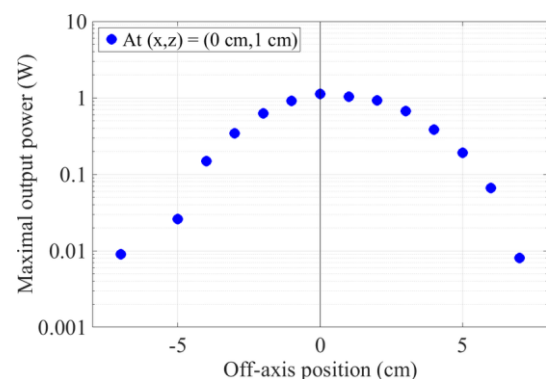


Figure 4: Maximal output power, as a function of the off-axis position.

3.3. Recharging of Commercial Devices

The output AC signal can be rectified into a DC signal using a diode bridge rectifier. A 5 V regulator (LM7805) is then implemented to provide a constant 5 V DC signal, necessary to recharge most conventional wearable devices, as described in Figure 5. Two printed-circuit boards are made and then used with two different receivers to power two different wearable devices simultaneously: an iPod Shuffle media player and a Garmin Vivosmart health monitoring watch. While simultaneously charging the two devices, as presented in Figure 6, at a frequency of 300 Hz, the DC power supplied to each device is measured to be 250 mW and 350 mW, respectively. It should be noted that the receivers are distributed at no particular location on the transmitter surface, nor the receivers windings are put in a particular orientation with respect to the transmitter coil.

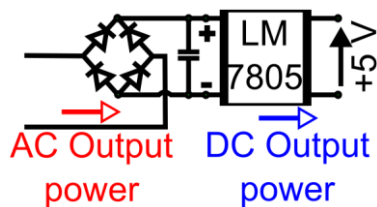


Figure 5: AC to DC conversion electrical circuit.

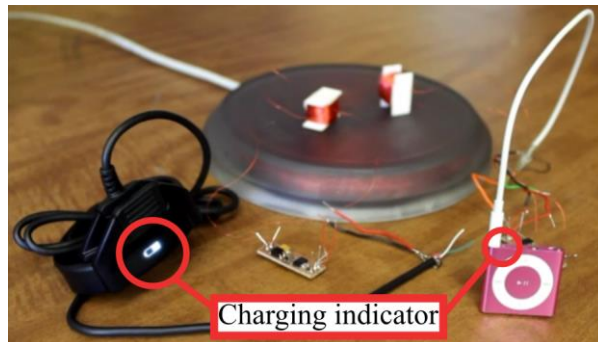


Figure 6: Demonstration of simultaneous charging of two commercial wearable devices: an iPod Shuffle and a Garmin Vivosmart health monitoring watch using two receivers.

4. Conclusions

In this paper, an EWPT system using the continuous rotation of a permanent magnet in the receiver is discussed. Compared to previous works, a significant improvement in the output power delivered to a resistive load is achieved, reaching up to 1.25 W, with a power density up to 350 mW/cm³ and an efficiency of 8 %. The on- and off-axis power deliveries from the transmitter, as well as powering multiple receivers at the same time, are demonstrated. The successful charging of two wearable devices placed in arbitrary positions and orientations demonstrates the potential application of this EWPT mechanism in consumer electronic products.

Acknowledgments

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