Electrodynamic Wireless Power Transmission to Rotating Magnet Receivers

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Abstract. This paper presents an approach for electrodynamic wireless power transmission (EWPT) using a synchronously rotating magnet located in a 3.2 cm^3 receiver. We demonstrate wireless power transmission up to 99 mW (power density equal to 31 mW/cm^3) over a 5-cm distance and 5 mW over a 20-cm distance. The maximum operational frequency, and hence maximal output power, is constrained by the magnetic field amplitude. A quadratic relationship is found between the maximal output power and the magnetic field. We also demonstrate simultaneous, power transmission to multiple receivers positioned at different locations.

1. Introduction

A century ago, before the electrical wire grid, Tesla developed and demonstrated the concept of electromagnetic wireless power transmission (WPT) [1]. Despite this early vision, it was only in the past ten years that WPT has received a surge of interest [2–4] due to the increasingly numerous and diverse power demands of mobile electronics devices (laptops, smart phones, tablets, wearables) in everyday life. Other application areas for WPT include automotive vehicle recharging [5] and the *in vivo* charging of biomedical implants [6]. The majority of efforts have relied on the electromagnetic coupling between two coils to wirelessly transfer the power, called inductive WPT. In this approach, a transmitter coil produces an alternating magnetic field that directly induces a voltage and current in a receiver coil placed at some distance away.

We have recently presented an alternative method, named electrodynamic wireless power transmission (EWPT) [7–9]. In this approach, a transmitter produces an alternating magnetic field that moves a permanent magnet in a receiver, the motion of which generates a voltage in the receiver windings. If a load is connected to the receiver windings, EWPT is achieved. The electrodynamic coupling solution affords operation at much lower frequencies (e.g. 100’s of Hz) than what is commonly used in inductively coupled WPT (e.g. 0.1 – 10’s of MHz). This low-frequency range of operation facilitates higher safety margins for magnetic field amplitudes [10,11] and better penetration (less attenuation) through electrically conductive media. Therefore, the EWPT method provides the opportunity to safely transmit power in crowded environments, such as a home, office space, automobile, or to an implanted biomedical device within the human body.

We have previously demonstrated the EWPT concept using mechanical resonance in the receiver magnet. A system employing a cantilever-based oscillator yielded a power transmission of 0.15 mW at

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2.2 cm [7]. A second prototype utilized a torsional resonator with an average transmitted power of 3.09 mW at 1 cm (equivalent to a power density of 143 µW/cm^3), and 0.126 mW at 7 cm [9]. System modeling has shown that a high mechanical quality factor in the receiver resonator is desirable for maximizing the power transmission and efficiency [8]. The inductive coupling between the transmitter coil and the receiver windings was previously shown to have a minor influence in the proposed EWPT scheme [9].

In this paper, an alternative motion in the receiver is explored. Rather than exciting a torsional resonance, the receiver magnet is continuously rotated by the transmitted B-field. Under steady-state operation, the rotating magnet acts as a synchronous machine, supplying electrical power to an external load. Compared to the resonant-type receivers, which only generated appreciable power when excited at their specific resonant frequencies, the rotational approach enables the receiver(s) to generate power across a wider frequency range of operation. As will be shown, this approach also enables much higher power transmission levels as well as simpler and more compact receiver construction. One limitation of this continuously rotating approach is that the receivers cannot instantaneously synchronize with the sinusoidal transmitter B-field. The machines take a certain amount of transient time to “start-up” from stand still, requiring a ramping of the transmitter frequency.

Section 2 first describes the concept of electrodynamic wireless power transmission through a continuously rotating magnet and it introduces the experimental setup used to perform EWPT. Section 3 discusses the experimental results. Conclusions are provided in section 4.

2. EWPT system design

2.1. Working principle

The EWPT system reported here includes two distinct parts: a coil-based transmitter and a receiver system featuring a permanent magnet rotor that is allowed to rotate within receiver windings, as illustrated in Figure 1.a. The transmitter coil is a thin solenoid with ~112 turns of 15-AWG copper wire, having an outer diameter of 30 cm, an inner diameter of 25 cm, and a length of 12 mm (L=8.5 mH, R=1.3 Ω). 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 (inspired by [12]) within a 3D-printed structure (diameter=25 mm, length=30 mm) with slots for coil windings, as presented by the schematic in Figure 1.b. In this prototype, the magnet and ferrofluid are held within a capped glass vial and centered via to plastic inserts. The receiver is wound with a single coil of 250 turns of 34-AWG copper wire. Figure 1.c presents a picture of the receiver system along with an example of capped glass vial containing a magnet covered by ferrofluid.

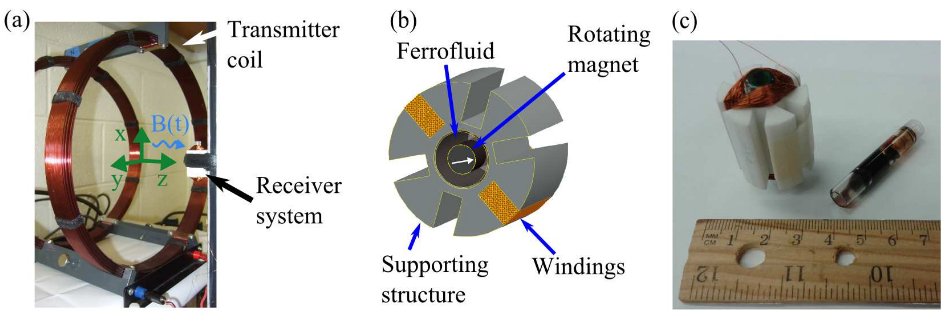

Figure 1: (a) Picture of the electrodynamic wireless power transmission system, (b) Cross-section schematic of the receiver system, (c) Picture of the receiver system and an example of the rotating magnet and capped glass vial containing the magnet and ferrofluid.

To transmit power, an alternating current is injected into the transmitter coil, which results in the generation of a time-varying magnetic flux density **B**(t). When the receiver system is placed nearby, the transmitted B-field applies an alternating torque that induces the synchronous rotation of the permanent magnet. The magnet motion produces a time-varying magnetic flux in the receiver windings thereby inducing a voltage. If an electrical load is connected to the two terminals of the receiver windings, power is delivered. Compared to a resonant-based system, the continuously-rotating EWPT has the potential to induce a larger variation of magnetic flux through the coil, since the magnet steadily rotates 360° around its axis at the frequency set by the transmitter AC current. Additionally, as described earlier, the receiver can operate across a large range of frequencies, the limits of which are discussed in Section 3.1.

2.2. Experimental setup
The EWPT system was characterized using the following setup. An HP33120A arbitrary waveform generator was used to supply an AC voltage to a Crown XLS2500 linear power amplifier. This produced an AC current input into the transmitter coil, monitored by a Tektronix TCP312A current probe connected to a Tektronix TCPA300 current probe amplifier. An Agilent DSO-X-2004A 4-channel oscilloscope was used to measure the input current to the transmitter, as well as the voltage measured across the receiver load. The resistance of the receiver windings was independently measured with a Keithley 2000 multimeter, using the 4-wire configuration. For a given AC excitation of the transmitter, the resultant B-field spatial distribution was measured with a Lakeshore XHMMA-1482 axial Hall probe connected to a Lakeshore 475DSP gaussmeter.

3. Results and discussion
First, the basic operation of the continuously rotating EWPT system was studied. Then, the output power as a function of the transmitted B-field was characterized along the central axis of the transmitter coil. Next, the off-axis wireless transmission was measured. Last, multi-receiver power transmission was demonstrated.

3.1. Basic Operation
After placing the receiver system at a certain distance from the transmitter, a fixed-amplitude 4 A_{RMS} sinusoidal current was injected in the transmitter coil, corresponding to 18.4 W. The resistive load was adjusted to 22.5 Ω to match the receiver windings resistance for maximum power transmission. The frequency was slowly increased from a low frequency, 40 Hz—where the receiver locked into synchronous, steady-state rotation—up to a point where the magnet lost synchronization with the transmitted B-field, resulting in no more magnet rotation. This upper frequency was 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 [13].

At a distance of z=4 cm between the center of the transmitter and of the receiver, the output power was measured at representative frequencies, as illustrated in Figure 2. We observed that the output power increased quadratically with the frequency (load voltage proportional to frequency), as expected with a synchronous machine, up to the maximum frequency of 295 Hz. The test was reproduced at several distances between transmitter and receiver. The results obtained at z=10 cm and z=20 cm are also reported in Figure 2. For a given frequency, the output power was found to be independent of the distance. However the maximal frequency, hence the maximal output power, were strongly dependent on the distance. The farther the receiver was from the transmitter, the lower the magnetic field, and the lower the maximum output power that was transmitted. The maximum output power was 66.4 mW at z=4 cm, but only 5.1 mW at z=20 cm. Consequently, in this configuration, a 5-fold increase in distance resulted in only a 13-fold decrease in the maximal output power.

3.2. Power vs. B-field

Keeping the transmitter current at 4 A_{RMS}, the distribution of the B-field along the z-axis was measured. Based on these measurements, the maximal frequency and the maximal output power were plotted as a function of the peak B-field, at discrete receiver locations along the z-axis. Figure 3 summarizes the results. A linear dependence was found between the maximal frequency and the transmitted B-field. Consequently, the maximal output power was found to be quadratic with B-field. Based on these observations, for maximal power transfer, the B-field from the transmitter should be as high as possible to increase the maximal frequency, hence the maximal output power, as long as it remains within safety limits.

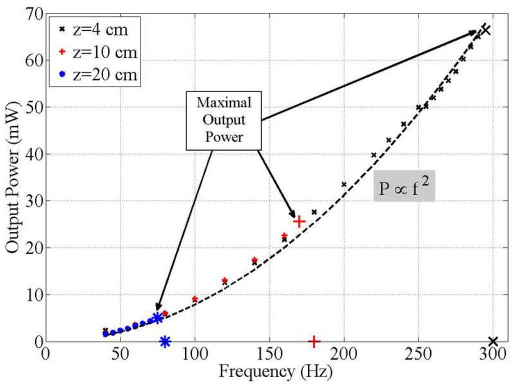

Figure 2: Output power vs. frequency, at different on-axis distances.

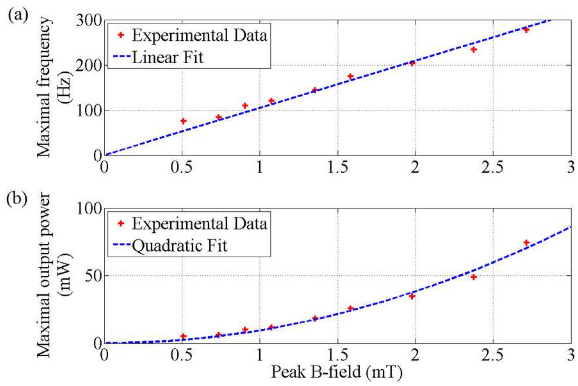

Figure 3: (a) Maximal frequency and (b) Maximal output power, vs. the transmitted peak B-field. Linear and quadratic relationships were found, respectively.

3.3. Off-axis wireless power transmission

Another capability for EPWT is off-axis power transmission. Due to symmetrical consideration, off-axis power was only measured for offsets in the positive y-axis. The receiver system was first placed at a distance z=6 cm away from the transmitter, and the off-axis distance y was modified. The resulting maximal output power as a function of y is reported in Figure 4. A maximal output power of 99 mW was measured at y=7 cm (z=6 cm). Numerical predictions of the expected output power levels at z=10 cm, z=15 cm, and z=20 cm are also plotted, based on the quadratic relationship with the peak B-field, found previously in Figure 3. The numerical estimations indicate that a reasonable output power can still be received off-axis, up to 20 cm away from the transmitter.

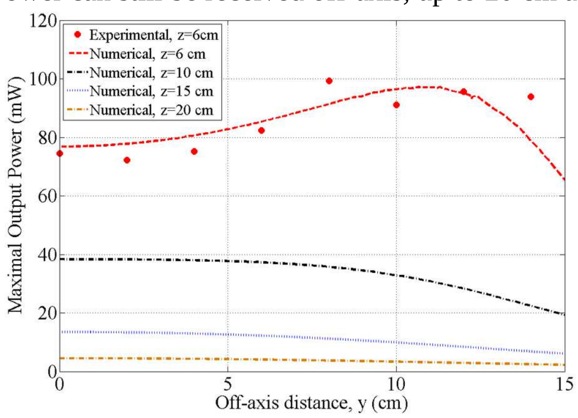

Figure 4: Experimental maximal output power vs. the distance y to the axis at z=6 cm and simulation results of the maximal output power vs. y at varying z distances.

3.4. Multi-receiver wireless power transmission

To test the ability to power multiple receivers, three similar receiver systems were placed in proximity to the transmitter. The EWPT system was shown to simultaneously power the three receivers distributed in space with no apparent limitation on their relative positions. As a worst-case scenario, the three receiver systems were placed one next to each other wherein maximum magnetic interaction could occur between the three receiver magnets. Even in this configuration, at a given frequency, each device received roughly the same amount of power as if powered alone. However, the maximal frequency was found to be lower (~ -30 %), causing a decrease in the maximal output power compared to the alone-receiver case.

4. Conclusion

In this paper, an EWPT scheme was presented using the continuous rotation of a permanent magnet, rather than resonant mechanical motion as presented in previous works. This approach resulted in a significant increase in the amount of power delivered to a resistive load, achieving up to 99 mW, with a power density up to 31 mW/cm^3. The system was shown capable of power a receiver off-axis from the transmitter, as well as powering multiple receivers at the same time. The maximal output power was demonstrated to be quadratic with the transmitted B-field. Future works will focus on improving the design of the receiver system to achieve a size reduction, as well as designing a transmitter coil with an improved B-field distribution.

Acknowledgments

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