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0.83-cm^3 240-mW electrodynamic wireless power receiver

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***Abstract*— In this paper, we present the modeling and experimental results of an electrodynamic wireless power transfer (EWPT) system based on a 0.83 cm^3 integrated receiver comprising a continuously rotating magnet. The measured normalized power density (143 mW/cm^3/mT^2) of our prototype is among the highest of the state of the art.**

Keywords—Electrodynamic wireless power transfer, EWPT, distant charging, continuously rotating mode.

I. INTRODUCTION

Electrodynamic wireless power transfer (EWPT) receiver are electromechanical systems that operate at very low frequency (usually less than 1 kHz). It consists in a mobile permanent magnet actuated by a low frequency magnetic field generated by a distant transmitter. The mechanical energy from the magnet is converted into electrical energy via an electromechanical transducer.

Several types of magnet movements can be exploited. The state of the art is mainly based on mechanical resonant systems using magnet attached to the tip of high quality factor piezoelectric cantilever beams [1], [2], or a receiver coil wound around a moving magnet mounted on spring [3]. These systems are very sensitive to weak magnetic fields, but are more fragile and have low power density. An alternative solution is to use a rotational system: the transmitter generates a magnetic field that drives a permanent magnet in continuous rotation. The receiver magnet can be driven at high speed (>50 rpm) resulting in a high power density.

In this work, we present a device based on a continuously rotating magnet. An analytical model of the device is developed and simulation results are compared to experimental performances.

II. OPERATING PRINCIPLE AND SETUP

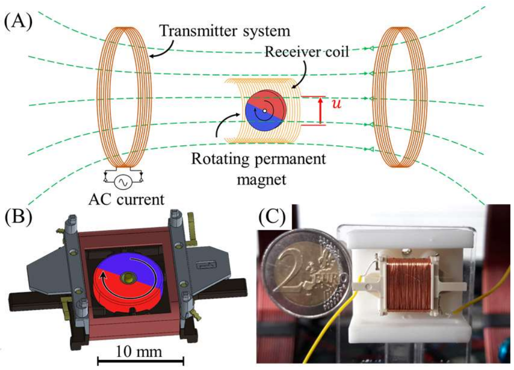

Fig. 1. (A) Principle of the electrodynamic WPT (EWPT) system based on a continuously rotating magnet in a receiver. (B) 3D view and (C) picture of the integrated electrodynamic receiver.

The power receiver used in this paper is based on a 0.83 cm^3 integrated generator from an autonomous wireless switch previously developed by our team [4] (Fig. 1). It comprises a diametrically magnetized magnet that rotates freely around its axis. A fixed receiver coil is wound around the magnet. The magnet rotates due to the varying magnetic field from a transmitter and generates a voltage at the terminals of the receiver coil. In order to characterize the performances of the receiver, it is placed at the center of Helmholtz coils acting as a transmitter. The receiver part is finally connected to a resistive load.

III. MODEL

An analytical model is developed to describe the behavior of the power receiver. The system is parametrized (Fig. 2) and an equivalent electrical circuit is inferred (Fig. 3).

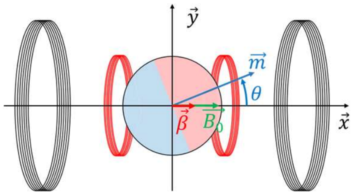

Fig. 2. Parameters for the analytical modeling of the electrodynamic WPT.

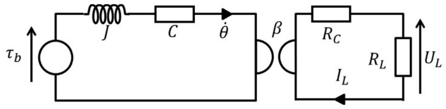

Fig. 3. Equivalent electrical circuit of the EWPT receiver.

The time-varying magnetic field of amplitude B_0 and frequency f generated by the transmitter coils is assumed to be uniform at the magnet location. It creates a torque τ_b on the permanent magnet depending on its magnetic moment m, and its angular position θ as defined in Fig. 2:

$$\tau_b = m\, B_0 \sin(2\pi f t) \sin(\theta) \qquad (1)$$

It is assumed that the direct interaction between the Helmholtz coils and the receiver coil is small (low coupling hypothesis), neglecting the backward effect of the receiver magnet on the transmitter coil. The rotation of the magnet in the receiver coil creates a time-varying magnetic flux leading to a voltage U_L on the resistive load R_L and a current in the receiver coil I_L , both depending on the electrodynamic coupling between the magnet and the receiver coil β, the resistive load and the internal resistance of the receiver coil R_c:

$$U_L = R_L I_L = \frac{R_L}{R_L + R_c} \beta \dot{\theta} \sin(\theta) \qquad (2)$$

The backward interaction between the receiver coil and the magnet also creates a torque on the moving magnet τ_E:

$$\tau_E = \beta I_L \tag{3}$$

The mechanical relationship between the torques and the angular moment are described by Newton's 2nd law, with C the coefficient and n the power describing the viscous damping:

$$J\ddot{\theta} = \tau_B - C\dot{\theta}^{\mathrm{n}} - \tau_E \tag{4}$$

This equation is solved thanks to Matlab Simulink. Parameters of the system presented in Fig. 1 are first identified. The winding resistance $R_c = 114\ \Omega$ is measured with an ohmmeter. The moment of inertia $J = 8.1\ kg\ m^2$ and the magnetic moment $m = 0.12\ Am^2$ are calculated from the magnet dimensions and material properties. $\beta = 10.2\ mNm/A$ is obtained by linking the rotation speed and the voltage amplitude in open circuit. Finally, a "let it roll" test [5] as seen on Fig. 4 is performed in open circuit to identify $n = 1.78$ and $C = 5.2\ nNms^{-n}$ on the curve.

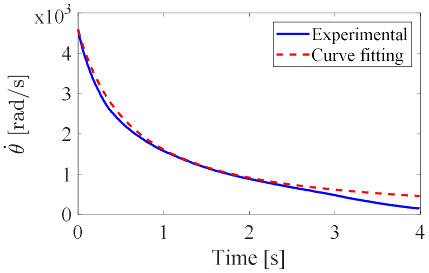

Fig. 4. "Let it roll" test in open circuit to identify the parameters C and n for the damping model $C\dot{\theta}^n$.

The model is implemented in Matlab Simulink as shown on Fig. 5. For a given load resistance, the frequency of the fixed amplitude magnetic field is swept up until pull out.

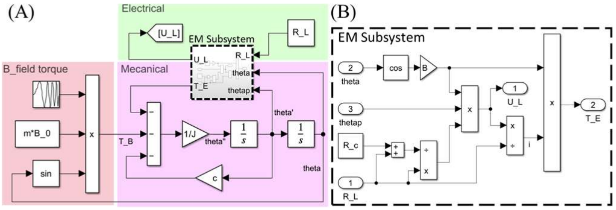

Fig. 5. (A) Matlab Simulink model of the receiver, and (B) electromechanical transducer subsystem.

IV. RESULTS

The increase of the frequency for a given resistive load leads to a quadratic increase of the output power until the magnet pulls out, as seen on Fig. 6.

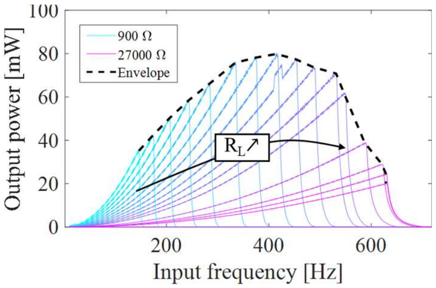

Fig. 6. Measured output power for different resistive loads and maximum power envelope for $B_0 = 1\ mT$.

Pull out occurs when the magnetic field is no longer high enough to counteract torques from the mechanical losses and the energy dissipation in the coil and load. Tests are carried out at different loads for a given field strength. Envelopes of maximum power are drawn from the maximum power points of each test, as shown on Fig. 6 for $B_0 = 1\ mT$.

Fig. 7 shows the maximum power envelopes for different amplitudes of magnetic field, both in simulations and experimentally.

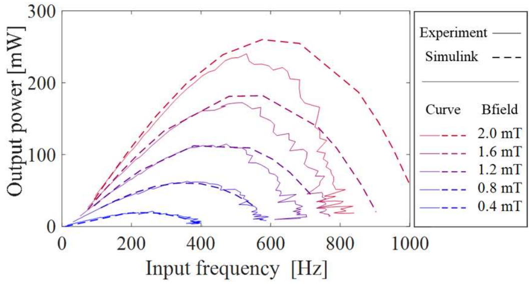

Fig. 7. Output power envelopes versus frequency and B-field amplitude.

There is a very good correlation for low magnetic fields (<1 mT). At higher fields, the experimental performances are lower than the theoretical ones for high frequencies. This seems to be due to a chattering phenomenon, which is audible at high frequency. Future improvements of the mechanical guidance should mitigate this phenomenon.

We measured an electrical output power of 19 mW with an output voltage of 11.5 V_{rms} for a field of 0.4 mT. This result leads to a normalized power density of 143 mW/cm^3/mT^2. For a higher field amplitude, power output of 240 mW with a voltage of 22.7 V_{rms} are obtained at 2 mT giving a normalized power density of 72 mW/cm^3/mT^2. AS far as the authors know, those power densities are among the highest of the state of the art.

V. CONCLUSION

This paper presents modeling and experimental results of an electrodynamic wireless power transmission system based on a rotating magnet. The power extracted from the device is 240 mW at 2 mT, even though an improvement of the mechanical guidance is necessary to better fit the model at high frequency. The model will allow us to better understand the dynamics of the system in order to optimize its progressive start-up.

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