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Highly-Efficient Wireless and Batteryless Switches for Home Automation

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***Abstract* — This paper reports on a highly-efficient electromagnetic energy harvester for wireless and batteryless switches. The energy harvester relies on a central rotating magnet driven by magnetic launchers and combined with a ferromagnetic circuit to take advantage of nonlinear behaviors and to increase the electromechanical conversion efficiency. The experimental output energy reaches 1.235mJ (350µJ/cm³) with a conversion efficiency of 56%, making it one of the most powerful and the most efficient in the state of the art.**

I. Introduction

Batteryless switches are among the most promising market for energy harvesting with millions of products per year targeted. Batteryless switches are aimed at converting the mechanical energy provided by a user into electricity to supply electronic functions that will allow to remote control lights, roller shutters or any home appliance. Several concepts of batteryless switches have been developed and some of them are commercially-available (ZF [1], EnOcean [2]). Their performances are overviewed in Table 1. However, the research on batteryless switches is still active to improve their performances and typically to: (i) reduce their size, (ii) increase their output energy and (iii) increase their efficiency to reduce the mechanical energy that should be provided by the user and then, to improve the user experience. The new concept of energy harvester for batteryless switches proposed in this paper is in line with these objectives.

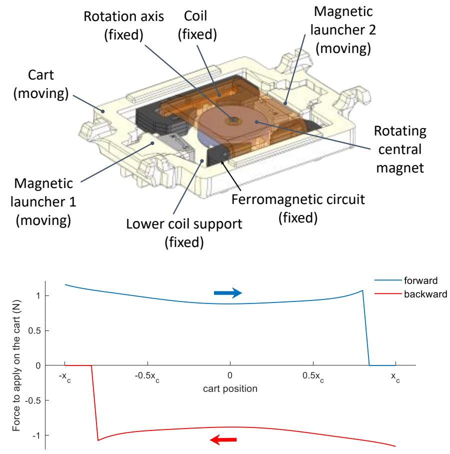
TABLE 1. Batteryless switches – state of the art

Reference	*Converter*	*EH size*	*Output Energy*	*Energy Density*
ZF [1]	Emag	2.33cm³	330µJ	141µJ/cm³
EnOcean [2]	Emag	3.99cm³	256µJ	64µJ/cm³
Algra [3]	Piezo	1.86cm³	10-50µJ	5-15µJ/cm³
Lu et al. [4]	Estat	0.446cm³	15.5µJ	34.7µJ/cm³
CEA (This work)	**Emag**	**3.5cm³**	**1235µJ**	**350µJ/cm³**

II. Energy harvester – concept, model and simulations

A. Energy harvester for batteryless switches – concept

The energy harvester (Figure 1a) is constituted of a central rotating magnet and magnetic launchers inserted in a cart and moving together in a translational motion relative to the center of the central rotating magnet. A coil is wrapped around the central magnet to convert its rotation into electricity. A ferromagnetic circuit, made of 4 U-shaped elements in silicon electrical steel is added to channel the magnetic flux lines outside of the coil. The ferromagnetic circuit induces a highly-nonlinear behavior and enables to store the mechanical energy provided by the user in a magnetic form until the repulsive force induced by Magnetic Launcher 1 (F_{rep_1}) becomes higher than the magnetic force between the central magnet and the ferromagnetic circuit (F_{fer}). Then, the energy harvester toggles and the mechanical energy stored in the system is delivered as oscillations of the central rotating magnet, which are converted into electricity with the coil.



(a)

(b)

FIGURE 1. (a) Energy harvester and (b) force to apply by the user to toggle the energy harvester with the two toggling points

The energy harvester has a symmetrical geometry and generates power on forward and backward movements, with two toggling points: x_{tf} and x_{tb} (Figure 1b), $x(t)$ being the cart position with regards to the rotation axis. The backward movement is equivalent to the forward movement, except that the initial state for the backward movement is the final state of the forward movement and the repulsive force is induced by Magnetic Launcher 2 (F_{rep_2}).

B. Model and parameters

Once $F_{rep_i} > F_{fer}$, the energy harvester behavior is ruled by the system of equations:

$$\begin{cases} J\ddot{\theta} = C_{elec}(\theta) + C_{mag}^{FEM}(\theta) + C_f(\theta) \\ e(t) = -\dfrac{L}{R_s + R_{load}}\dfrac{de(t)}{dt} - N\dfrac{d(\phi_u^{FEM})}{d\theta}\dfrac{d\theta}{dt} \end{cases} \qquad (1)$$

With : θ the angular position of the central magnet, J the mass moment of inertia of the central magnet, N the number of turns of the coil, L its inductance and R_s its series resistance. R_{load} is the resistive load connected to the coil to extract the electrical power. $e(t)$ is the voltage across $R_s + R_{load}$, $C_{elec}(\theta)$ the electrical torque modeling the extraction of electrical energy: $C_{elec}(\theta) = \frac{e^2/(R_s+R_{load})}{\dot{\theta}}$. C_f is the friction torque : $C_f = c_f\dot{\theta}$ modelling mechanical losses. ϕ_u^{FEM} is the magnetic flux induced by the magnet in the coil and $C_{mag}^{FEM}(\theta)$ the magnetic torque due to the ferromagnetic circuit, and are both obtained with finite element simulations.

C. *Simulations*

ϕ_u^{FEM} and $C_{mag}^{FEM}(\theta)$ have been determined with 3D electromagnetic finite element simulations and implemented in a Simulink model solving equation (1). The output voltage and the output energy are presented in Figure 2 and show that 1.270mJ can be theoretically reached. As previously mentioned, the rotation of the central magnet is followed by oscillations : each of these oscillations generates a variation of magnetic flux in the coil and an electromotive force, resulting in an AC voltage at the output of the energy harvester.

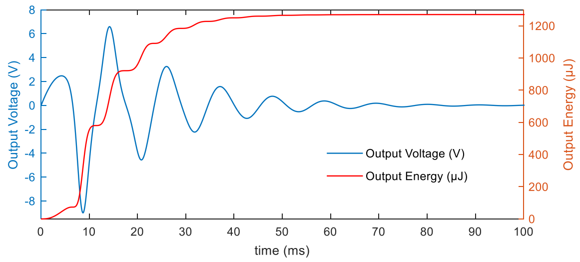


FIGURE 2. OUTPUT VOLTAGE AND OUTPUT ENERGY (SIMULATIONS) – FORWARD MOVEMENT

III. ENERGY HARVESTER – PROOF OF CONCEPT, EXPERIMENTAL RESULTS AND MECHANICAL INTEGRATION

A. *Proof of Concept*

A proof of concept has been developed and is presented in Figure 3a, with its constitutive elements in Figure 3b. Magnets are in NdFeB. The coil is a winding of 1250 turns of 80µmØ copper wire. Plastic pieces have been manufactured by plastic injection by using injection molds. The energy harvester has a size of 30.5mm×21mm×5.5mm=3522mm³.

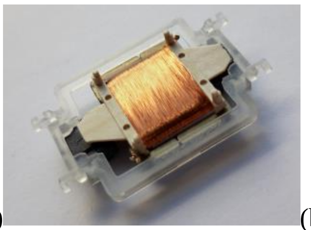
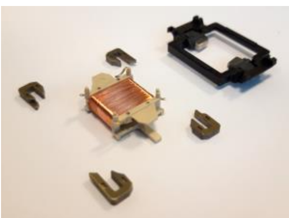
(a)  (b) 

FIGURE 3. (A) PROTOTYPE AND (B) CONSTITUTIVE ELEMENTS

The experimental output voltage and output energy are presented in Figure 4. As predicted by the simulations, the experimental output energy reaches 1.235mJ (350µJ/cm³) in 60ms. The energy provided by the user is 2.2mJ with a force to apply of roughly 1N. This corresponds to a conversion efficiency of 56%, made possible thanks to the topology chosen for the energy harvester with the coil directly wrapped around the rotating magnet.

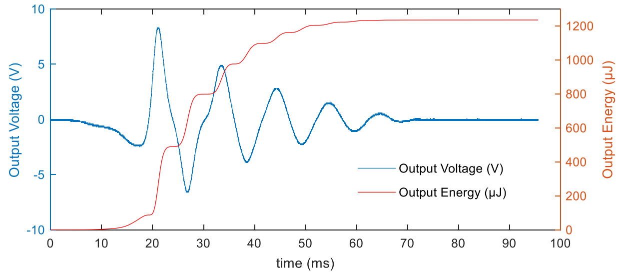


FIGURE 4. EXPERIMENTAL OUTPUT VOLTAGE AND OUTPUT ENERGY – BACKWARD MOVEMENT

B. *Mechanical integration and power supply of electronic functions*

The energy harvester is integrated within a mechanical switch (Figure 5). The actuation mechanism within the switch converts the pressure imposed by the user into a translation movement of the cart and then, into electrical energy. The energy is used to supply the electronic functions on a PCB inserted in the switch, and sending RF commands. A diode-bridge-capacitor circuit is used to turn the raw AC voltage provided by the energy harvester into a DC supply source for the microcontroller and the RF chip (Zigbee Green Power© SoC).

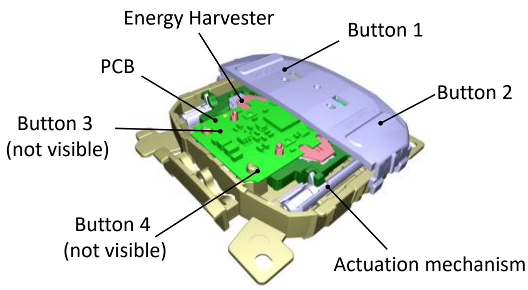


FIGURE 5. MECHANICAL INTEGRATION OF THE ENERGY HARVESTER

IV. CONCLUSIONS

We have presented a new concept of energy harvester for batteryless switches showing one of the highest output energy (1.235mJ) and the highest output energy density in the state of the art (350µJ/cm³). This technology has been transferred to industry with a commercialization forecasted in 2021 [5].

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