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Magnetolectric Energy Harvester and its Power Management Circuit to Regulate Indoor Air Quality

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Abstract—In this work, we present the next generation of magnetolectric energy harvesters developed by Enerbee Technology, and the associated power management circuit that was developed by CEA-Leti. Enerbee Technology develops a self-sufficient and connected product embedded with sensors for the regulation of indoor air quality in non-residential buildings, providing a low maintenance solution to increase the health and well-being of both the structure and the occupants, for the whole lifetime of the infrastructure. In this new generation of energy harvester, the piezoelectric part of the energy harvester has been optimized to better extract charges from the material. Therefore, a $3.4\times$ size reduction is achieved while maintaining the same harvested energy. On the electronic side, we report a power management circuit based on a low-power implementation of a non-linear extraction technique by controlling a Flyback converter with a microcontroller unit: energy extraction occurs at the maximum voltage of the magnetolectric harvester, allowing more power to be harvested compared to standard circuits. Compared with the standard energy harvesting interface, a power gain up to 1.75 is measured at a frequency of 47 Hz, and a Flyback efficiency up to 80 % is reported for a total power of 0.5 mW.

Index Terms—power management circuit, microcontroller, magnetolectric, piezoelectric, energy harvester, HVAC, indoor air quality

I. INTRODUCTION

According to the 2020 Global Status Report for Buildings and Constructions of the United Nations, buildings account for 35 % of the energy usage and 38 % of the emissions, representing ~ 55 % of the worldwide electricity consumption [1]. Zooming in the usage repartition, the Heating, Ventilation and Air Conditioning (HVAC) usage represented 52 % of the total consumption in the U.S. commercial buildings in 2018 (32 % for H, 11 % for V, and 9 % for AC) [2]. Thanks to regulations, insulation in buildings have improved inducing

less and less thermal leakages between indoor and outdoor, thus lowering heating and cooling energy consumption. However, the improved air tightness has reduced the amount of air infiltrating the building. In consequence, indoor air quality has been deteriorated whereas fresh air is essential for the health of buildings and their occupants. While adding good ventilation systems is necessary to improve air quality, it is not necessarily linked to a significant increase of energy consumption. Since rooms in buildings are not used all the time at full capacity, substantial energy savings could be made on ventilation usage if the monitoring and control of indoor air is able to provide the right air quality and quantity in the right place at the right time. Therefore, air quality has to be monitored in each room with appropriate sensors (*e.g.* occupancy, humidity, temperature, CO₂ or VOC rate) to control air renewal.

Enerbee Technology, as part of the F2A Group, a French supplier of HVAC solutions for non-residential buildings, has developed and commercialized the e-VAV product [3] shown in Fig. 1.a. It comprises an energy harvester (EH) that collects sufficient energy from the airflow in air ducts to closely monitor air quality from a set of embedded sensors, and to directly act on the renewal airflow rate to provide fresh air whenever it is needed.

Recent optimization of the EH architecture (Section II-B) have led to a drastic modification in the EH output characteristics, requiring a redesign of the Power Management Circuit (PMC). Indeed, PMCs implementing efficient extraction techniques are important elements not only to convert the high voltage and alternative output of the harvester into a usable form (typically 3 V DC) but also to optimize the energy extraction of low-power energy sources. In this paper, we also report the implementation of the Multi-Shot Synchronous

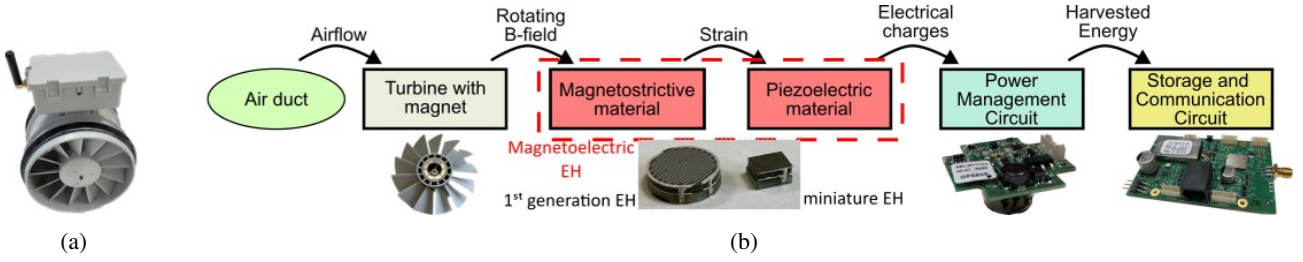


Fig. 1: (a) Picture of the e-VAV and (b) working principle of the magnetolectric EH, showing the e-VAV components.

Electric Charge Extraction (MS-SECE) technique with a Microcontroller Unit (MCU). The main goal of the paper is to show that implementing efficient non-linear extraction techniques controlled by MCUs is an interesting and more flexible alternative to Application Specific Integrated Circuits (ASICs). After a description of the EH (section II) and the proposed PMC architecture (section III), their combined performances are given in section IV.

II. MAGNETOELECTRIC ENERGY HARVESTER

A. Working principle

The working principle of the e-VAV product is presented in Fig. 1.b. The EH, located on the stator, is made of a stack of a magnetostrictive layer placed between two piezoelectric layers. The stack is placed on a PCB for mechanical support and electrical connections [4]. The rotation of a magnet attached to the turbine contactlessly induces strain in the magnetostrictive layer, deforming in turn the piezoelectric layers, resulting in electric charge generation. Charges are stored in the Storage and LoRa Communication Circuit, which powers the Sensors Circuit (not shown), directly acts on the airflow and regulates the indoor air quality.

On the first generation version, interdigitated electrodes on both piezoelectric end faces collect free charges (Fig. 2.a). One of the major drawbacks of the double-side interdigitated electrodes pattern is that it creates “dead zones” where the electric field lines do not cover the entire volume, lowering the EH efficiency [5].

B. Miniaturization and Optimization of the Energy Harvester

We have proposed an improved version of the magnetolectric EH to overcome the dead zones issue [6] by implementing a piezostack configuration (Fig 2.b). The miniature EH, shown in Fig. 1.b, results in a $3.4\times$ size reduction from the first generation EH, while harvesting the same energy. Since the electrodes go through the whole material thickness, the electric field lines are homogeneous and collect all generated charges throughout the piezoelectric volume. Compared to the first generation version, this new architecture comes with a $60\times$ capacitance increase and a $10\times$ decrease of the output voltage, greatly simplifying the associated PMC.

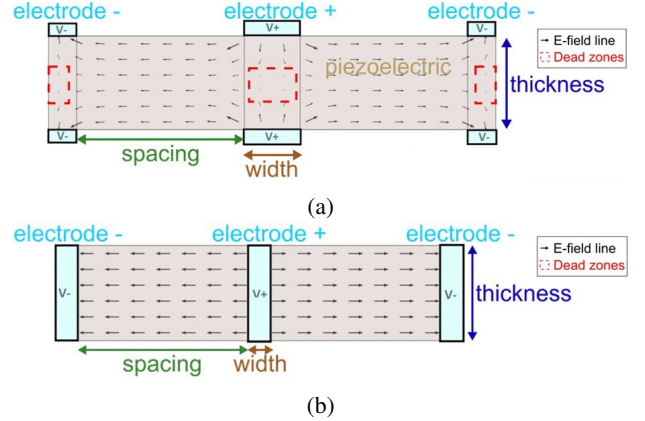


Fig. 2: Electric field distributions depending on the piezoelectric configurations: (a) interdigitated electrodes for the first generation EH and (b) in-volume electrodes, also known as piezostack, for the miniature EH (EHs not to scale).

III. POWER MANAGEMENT CIRCUIT STAGE

A. Input Specifications

For the PMC part, we have only considered that the piezoelectric part of the EH, having an intrinsic capacitance C_p in the [80 nF - 120 nF] range is alternatively compressed and stretched in quasi-static mode. The PMC must address rotation frequencies down to hundreds of rpm (a few hertz) and up to ~ 3000 rpm (~ 50 Hz). We made the choice to implement a specific non-linear extraction technique to improve both the extraction and conversion steps [7] compared to the standard energy harvesting (SEH) technique which involves a full diode bridge rectifier (FBR) followed by a filtering capacitor.

B. Extraction technique

The proposed PMC is based on the MS-SECE extraction technique [8], an improved version of the well-known SECE [9] technique. As shown in Fig. 3.a, the energy extraction happens at the same moment in the cycle as that of the SECE, *i.e.* at the maximum of the EH output voltage. However, in the case of a MS-SECE, instead of extracting the energy at once, it is extracted in N successive “shots”, each transferring the same amount of energy. Like the SECE, the MS-SECE is theoretically up to four times more efficient than the SEH technique, *i.e.* a FBR operating at its optimal voltage. Furthermore, the extracted power of the MS-SECE and SECE are

independent on the voltage across the storage element. Paing *et al.* [10] have already proven the feasibility of powering the SECE technique with a MCU, but as far as we know, no MS-SECE has ever been implemented with such component. The overall schematic of the proposed PMC is depicted in Fig. 3b, showing the power path (FBR and Flyback), the Maximum Voltage Detector block mainly used to detect the maximum EH voltage and the MCU implementing the MS-SECE. By successively driving the primary (K_p) and secondary (K_s) MOSFETs of a Flyback converter, the MS-SECE technique enables to i) improve the efficiency of the energy transfer as compared with SECE or ii) make possible to reduce the volume of the PMC at constant efficiency. Furthermore, the coupled inductor of the Flyback allows to easily control all the MOSFETs switches.

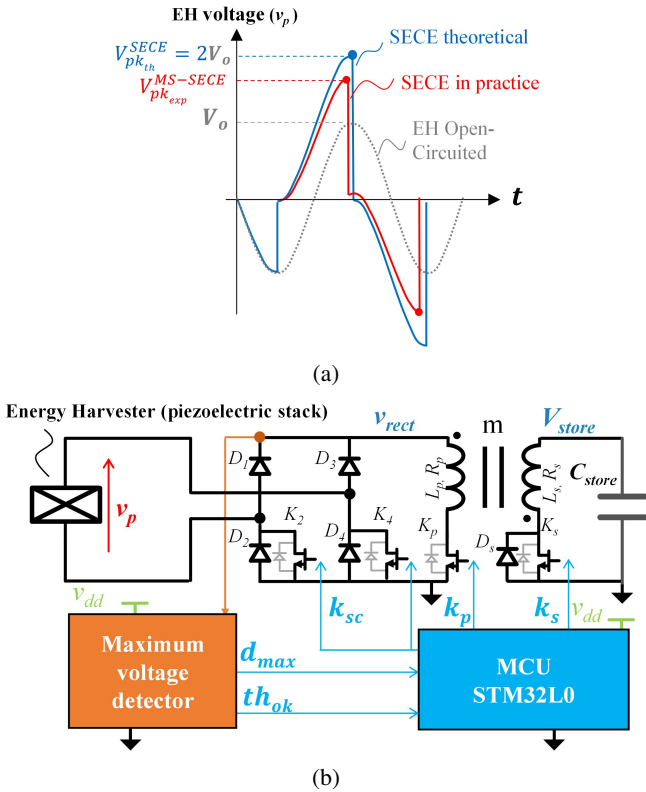


Fig. 3: (a) SECE voltage waveforms and (b) overall architecture of the proposed PMC (cold-start function not depicted).

The important signals of the proposed circuit are depicted in Fig. 4. One can note that the EH is discharged in N successive shots after the maximum detection (d_{max}) goes high. One can note that the closing durations of K_p at the primary must increase successively from a shot to another in order to store the same amount of energy for every shot in the coupled inductor. Because parasitic oscillations of v_p can occur in a real situation (noise, vibration), the extremum detections are ignored during the MS-SECE phase and when v_p goes below a fixed threshold, avoiding any EH discharges at inopportune moments. Two additional MOSFETs (K_2) and (K_4) are used to short-circuit the EH right after its discharge for the next

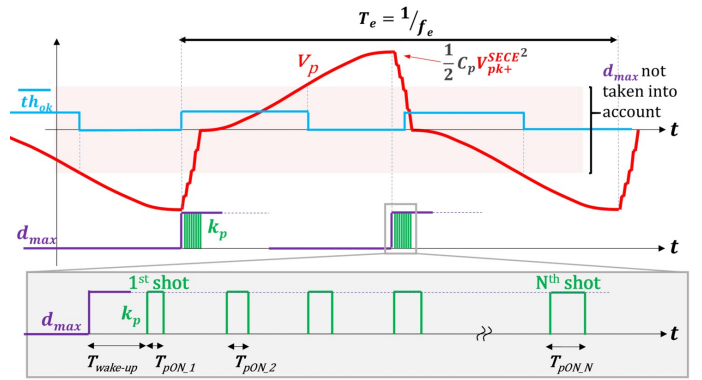


Fig. 4: Ideal voltage waveforms of the circuit showing two N -shots MS-SECE discharges performed during a complete electrical period T_e . The control of K_s for the Flyback secondary phase is not depicted in this graph.

deformation to start at $v_p = 0$, which enhances the harvestable power particularly at very low frequencies ($f_e < 10$ Hz).

C. PMC Implementation

We used a low-power MCU (STM32L011) to implement the MS-SECE technique associated with a low-level programming to optimize the power consumption of the system. Most of the time, the MCU is in STOP mode until it wakes up to a RUN mode using its 16 MHz internal oscillator to precisely control K_p and K_s with a ~ 60 ns resolution. Right after the N -shot discharge, the MCU gets back to its STOP mode and inactivates the oscillator. A second, low-frequency and imprecise ~ 37 kHz clock is however used all the time with the aim of generating the short-circuit duration to drive K_2 and K_4 with the control signal k_{sc} . For the "Maximum Voltage Detector" block, we employed a RC-differentiator followed by a zero-crossing function based on a comparator (MAX9119) to detect the maximum voltage of v_p . The threshold detection block is implemented with a low-power comparator (TLV3691-TI) surrounded by discrete components. Fig. 5 shows a temporal measurement example of a 16-shot discharge performed by the MCU.

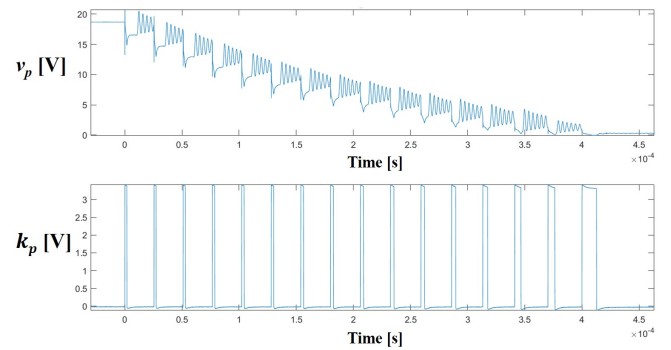


Fig. 5: Measured waveforms (PEH voltage v_p and Flyback control signal k_p) during a 16-shot discharge ($f_e = 30$ Hz).

IV. RESULTS

The PMC has been tested with the miniature EH. Its rotation frequency was set on a dedicated test bench by a brushed DC geared motor, leading to an electrical frequency f_e in the [1 Hz - 50 Hz] range. For those experiments, an independent power source was used to supply the PMC, including the MCU. The peak open circuit voltage V_0 of the EH (see Fig. 3.a) was 19.4 V (independently from f_e) and its capacitance $C_p = 36.5$ nF. Fig. 6 shows the test PCB (inset) embedding all the necessary components with additional test points. We estimated that PCB size could be reduced to a ~ 3 cm \times 3 cm area.

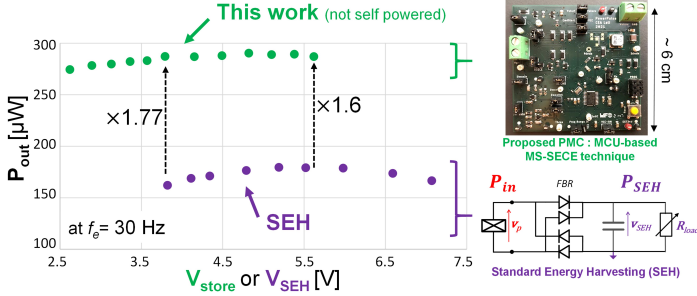


Fig. 6: Electrical output power: proposed PMC vs SEH technique at a frequency of 30 Hz. Inset: test PCB of the proposed PMC.

Fig. 6 also shows the output power of the PMC measured on C_{store} (i.e. for various V_{store}) at $f_e = 30$ Hz. The power gain (i.e. $\frac{P_{store}}{\max(P_{SEH})}$) for this specific case is 1.6 ($P_{store} = 300$ μ W) compared to an optimized SEH technique ($V_{SEH} = 5$ V). We also observe that the power gain is around 1.4 at $f_e = 8$ Hz ($P_{store} = 60$ μ W) and 1.75 at $f_e = 75$ Hz ($P_{store} = 500$ μ W). At $V_{SEH} = 3$ V, a gain of 2.14 has been measured at $f_e = 75$ Hz. We measured a Flyback efficiency around 75%-80% for a 16-shot discharge.

The attentive reader may notice that the gain in practice is lower than 4, which is the theoretical gain of the SECE technique in the case of a lowly coupled PEH harvester [9], compared to an optimized SEH technique. This is not entirely explained by the Flyback efficiency. Indeed, we observed that V_0 (see Fig. 3a), when the MS-SECE is activated, is not increased by a factor of 2 as expected, but rather by a factor of 1.1 to 1.6 depending on f_e . This is probably due to the fact that the material deformation amplitude is not fully imposed, particularly during the sudden MS-SECE discharge. A variation of the EH capacitance during its deformation could also explain such behavior.

The power consumption of the whole PMC is dependent on the input frequency (f_e) and is around 7 μ W/Hz for a 16-shot discharge performed 2 times per electrical period. It has a static consumption of ~ 10 μ W at $V_{dd} = 3.3$ V. The proposed PMC consumes around 6 % to 16 % of the electrical input power depending on the miniature EH characteristics (capacitance and open-circuit voltage V_0).

Finally, we observed a significant increase of the harvestable (and harvested) power in the low-frequency range ($f_e < 10$ Hz) when the short circuit function is activated. A specific measurement example is shown in Fig. 7 where the harvestable power is increased by 1.3 at $f_e = 8$ Hz thanks to this additional function. For frequencies higher than $f_e = 10$ Hz, the power improvement of the short circuit function becomes insignificant. Those measurements show that the SC function must be dynamically adapted (i.e. the short circuit duration) in operation to fit the large frequency range of the targeted application.

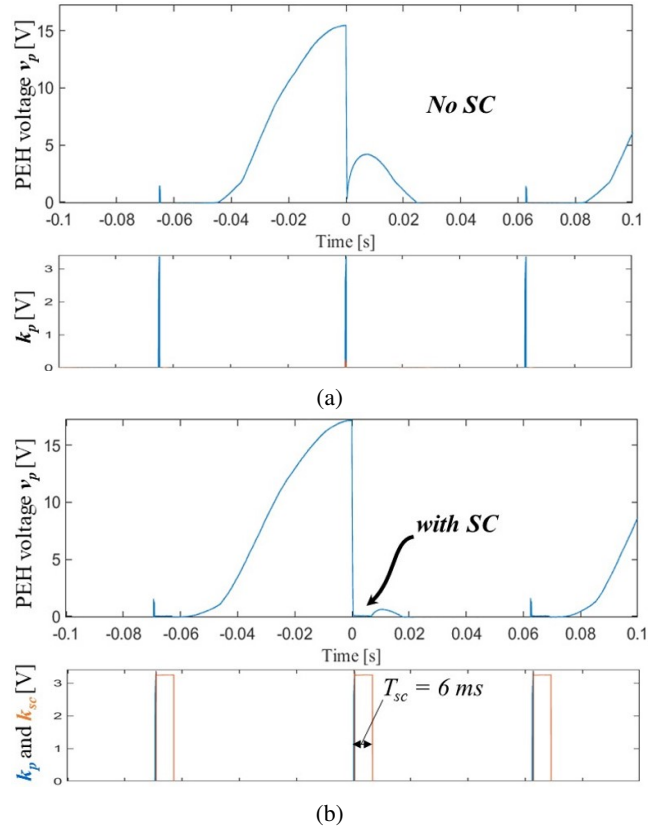


Fig. 7: Measured waveforms during a 16-shot discharge at $f_e = 8$ Hz with (a) no short-circuit and (b) with short-circuit.

V. DISCUSSIONS

We present the optimization of an entire energy harvesting system, encompassing both the EH component and the PMC part, with the goal of achieving energy self-sufficiency for an indoor air quality self-regulation system. The proposed PMC is versatile to any change of harvester characteristics (EH capacitance and open-circuit voltage) and seems very well suited for applications that have not yet reached a mass market (often justifying ASICs). It is now necessary to design a cold-start function to bootstrap the PMC, allowing it to start operating from a no-energy state. This has previously been done in prior art, by using, for example, comparator-based voltage supervisors combined with a normally-on MOSFET [8], [11].

As a perspective, a dynamic optimisation of the short-circuit duration and the number of shots of the MS-SECE (efficiency vs power consumption) in operation must be investigated. This potential improvement will open a way towards an optimization with, for instance, intelligent maximum power point tracking algorithms implemented by the MCU in a very low-power manner. Finally, integrating the PMC functions and the sensor system within the same MCU appears to be an interesting optimization from a cost and area standpoint.

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