Standalone Power Management System for Flexible Piezo Electric Nano Generators (PENG) Based on the Co-Polymer P(VDF:TrFE)

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Keywords

«Piezo actuators», «Maximum power point tracking», «Power management», «Energy harvester».

Abstract

This paper presents the design and manufacturing of a PENG based on flexible PVDF. The power management system (PMS) used to convert its ac voltage into a dc one, providing MPPT is presented. The system is tested to cover two use cases, namely energy storage in a battery and in a standalone configuration. The PMS is able to produce adjustable output voltages ranging from 0.8V to 1.5V.
With a regulated 1.5V the PMS is capable of producing up to 900nJ of energy from bending single deformation of the harvester. The PMS can harvest as low as 1.4µW from the PENG. A low power MPPT system, consisting of a single comparator is shown. In addition, insights about selecting optimal input capacitance of the PMS under different use cases is given in this paper. The MPPT technique improved the harvested output power by up to 44%.

Introduction

The Internet of Things (IoT) is the talk of the town, in which self-sustainable autonomous sensors and battery systems have gained popularity for everyday life. Energy harvesting (EH) technology can play a major role in realizing these standalone sensors and battery systems [1]-[3]. Energy harvesting has been attracting attention for a long time now, due to its ability to power small sensor nodes without the need of a battery or direct power connection [4]. Among EH concepts, piezoelectric nanogenerators (PENG) have the advantage of a simple design and high integration density. Usually such generators are made of piezoelectric ceramics like PZT, but these are brittle and due to their stiffness possess a high resonance frequency [5]. Polymer-based PENGs, in contrast, are a flexible alternative for harvesting at lower frequencies and outputs close to 1 mW have been shown [8]. In addition, they are lead free [6] and can be realized with low costs in a large area with techniques like roll-to-roll (R2R) or screen printing [7]. Energy harvesting from these polymer-based PENGs could be one of the potential sources for low-power devices, because of its sheer advantages in the form of flexibility, good stability, and its ease of handling and shaping [9]. A solution to make these low-power devices autonomous is by extending battery-operating time by storing the energy harvested from the PENGs along with achieving maximum power point tracking (MPPT) for higher efficiency. A major application that could benefit by extending the battery operating time is embedding a wearable energy harvesting device in everyday activities of athletes. These wearable energy harvesters can be implemented in shoes [10, 11], bags [12, 13], and clothing [14-16].

In this work, a piezoelectric energy harvesting system has been developed, by translating mechanical energy into electrical energy and rectifying the electrical energy into a regulated dc output voltage using a power management system (PMS). An important aspect of this application is that the higher power loads require both an EH and a battery, whereas lower power loads can be sufficiently powered by an EH alone. This requires a PMS that can handle both, battery-powered and battery-less systems. Hence, two application specific cases have been discussed in this paper to cover a wide range of energy harvesting applications, along with considering the overall size of the PMS to make it cost effective. A series of experiments are performed to characterize these harvester prototypes, proving that the harvester can serve as a wearable power supply for low power applications. Maximum power point tracking results in tuning the design to operate at the point where the EH produces its maximum energy and has its highest efficiency [17]. Hence, the MPPT feature has been implemented in the PMS to maximize the harvested energy. To combat the high power consumption of typical micro controller based MPPT implementations, a design using a simple circuit is utilized [21]-[25].

Flexible Transducer Fabrication and Characterization

The flexible ferroelectric transducers were fabricated in a capacitor-like structure on a 125 µm thin PET substrate as shown in the schematic in Fig. 1. The transducer structure was fully screen-printed and comprises a layer of the ferroelectric co-polymer P(VDF:TrFE)80:20 sandwiched between two layers of PEDOT:PSS electrodes as displayed in Fig. 1. Due to its piezo- and pyroelectrical characteristics, P(VDF:TrFE) can detect changes in stress, strain and even temperature. P(VDF:TrFE)-based transducers can convert a part of the mechanical/thermal input energy into electrical energy and this transducer property can be exploited for energy harvesting devices that transduce waste mechanical to electrical energy. The energy output of a flexible transducer (PENG) during periodic manual bending is shown in Fig. 1b. By varying the external resistance, the maximum output power P_{out} reached 25 µW for an optimum load resistance R_L = 6.9 MΩ, corresponding to a peak power density of 14 mW/cm3.

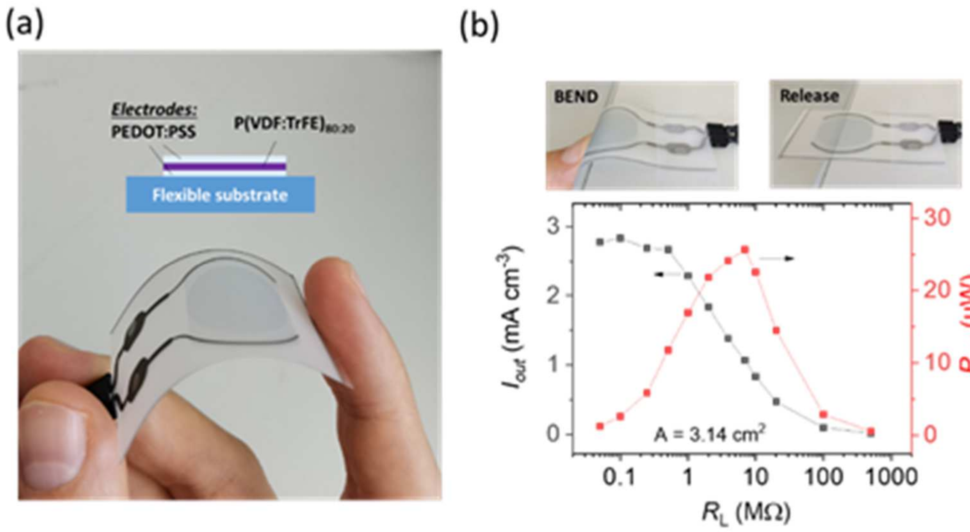

Fig. 1: Flexible P(VDF:TrFE)-based transducers. a) Photograph and schematics. b) Energy output by periodic manual bending: The current density of a random sample, I_{out}, as well as the corresponding output power, P_{out}, are plotted as a function of load resistance R_L.

Power Management System Practical Implementation

The PMS is developed based on the following block shown in Fig. 2 for a standalone and battery storage system. The energy source used for realizing the design is a polymer-based PENG which works on mechanical vibration and strain energy. Piezoelectric generators can generate high output voltages [18], up to a few volts. However, due to their small current characteristics, only in Microamps, they produce relatively low output power [18]-[20]. Hence, low leakage diodes and a very low quiescent current buck converter are utilized, resulting in a lower ambient current consumption of the harvester system.

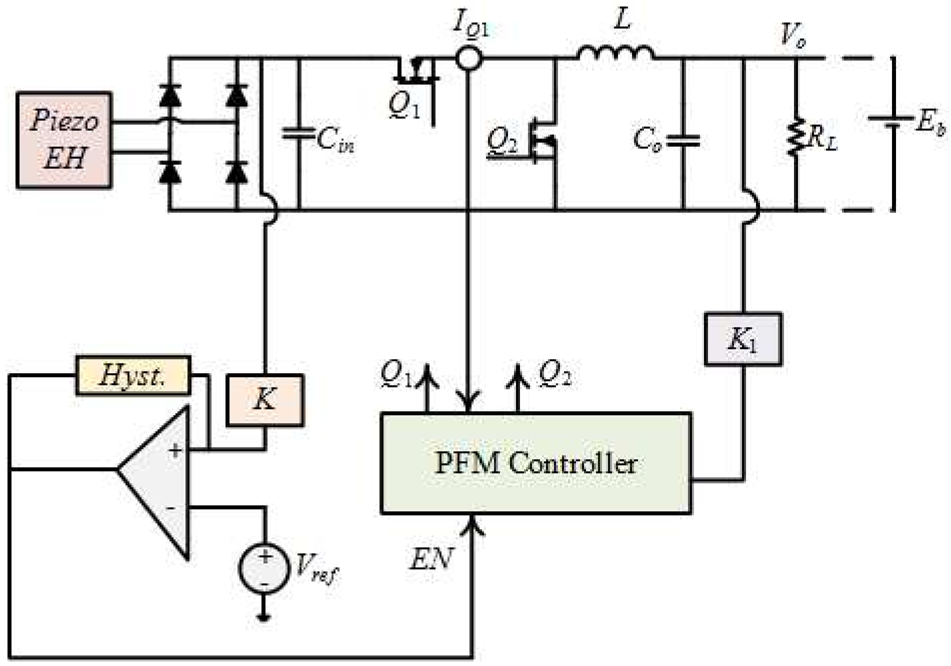

Fig. 2: Block diagram of the PMS.

The PMS system is composed of a PENG, a full-bridge rectifier, MPPT circuit with voltage divider (*K*) and comparator, a dc-dc buck converter with pulse-frequency modulation (PFM) control and a battery/load. The Piezo EH is modeled as an equivalent circuit consisting of a sinusoidal current source, a capacitor, C_p, and a large resistor, R_p, [26, 27]. The PENG's sinusoidal and random vibrational outputs are rectified through the full-bridge rectifier by converting the ac output into a dc one. Four low leakage diodes are used to realize the full-bridge rectifier.

As mentioned, the converter is realized with a pulse-frequency modulation (PFM) controller resulting in higher efficiency at light loads. PFM mode allows the buck converter to vary the switching frequency according to the load, ensuring that the inductor current always remains positive. This results in lower conduction losses compared to the conventional continuous conduction mode of operation (CCM), as well as provides the advantage of reduced switching losses due to the switching frequency decreasing with the load current. The rectified voltage from the PENG will charge the input capacitor C_{in} of the dc-dc converter up to ideally the open circuit voltage of the PENG, V_{oc}, if the converter is disabled. The energy harvested accumulates on the input capacitor C_{in}, until it is transferred by the buck converter to the output capacitor, C_o. Once the voltage across the input capacitor exceeds the predetermined reference, the buck converter is enabled and a regulated output voltage can be achieved. Hence, a high voltage and low-current output from the energy harvester is converted to an adjustable low-voltage (0.8V-1.5V) output for the standalone usage/or battery storage system. Low C_{in} and C_o capacitances are selected accordingly to start the buck converter with minimum current consumption, although resulting in a ripple-regulated output voltage, which is desired for a correct PFM and MPPT operation.

Maximum power transfer of a PENG occurs when the electric load matches the internal impedance of the energy harvester or, when the voltage across the electric load is half of the rectified open-circuit voltage, V_{oc}. Unlike more power-hungry solutions, the implementation of MPPT described in this paper has been achieved with only a voltage divider and a comparator. Through the electrical characteristics of the PENG shown above, it was determined that after rectification (1V drop across each diode), maximum power can be extracted at around 3V. Hence, the inverting input of the comparator is set to 0.2V (V_{ref}) and the non-inverting input of the comparator is fed through a voltage divider gain (*K*), comprising of two series-connected resistors. As the rectified voltage charges C_{in}, the divider output voltage also increases accordingly. Once the divider voltage goes above the reference voltage, the comparator provides an enable signal, resulting in the turn-on of the buck converter. C_{in} starts discharging by transferring energy to C_o, hence, the divider voltage drops below V_{ref}. Then, the EN signal gets driven low from the comparator, resulting in the converter shutting down. C_{in} charges back to its maximum value, maintaining the optimum voltage from the PENG.

Optimization of the Input Capacitor

In order to find the optimal input capacitor value for the harvesting circuit, several measurements were taken and evaluated. Since the buck converter is basically disconnected until the enabling voltage is reached, the load of the harvester circuit in this phase can be modeled as the rectifying stage plus the input capacitor. To find the local MPP of this circuit, the harvester was excited continuously using a shaker and the output power was calculated. Figure 3 shows the output power of the harvester for different input capacitance values with varying loads.

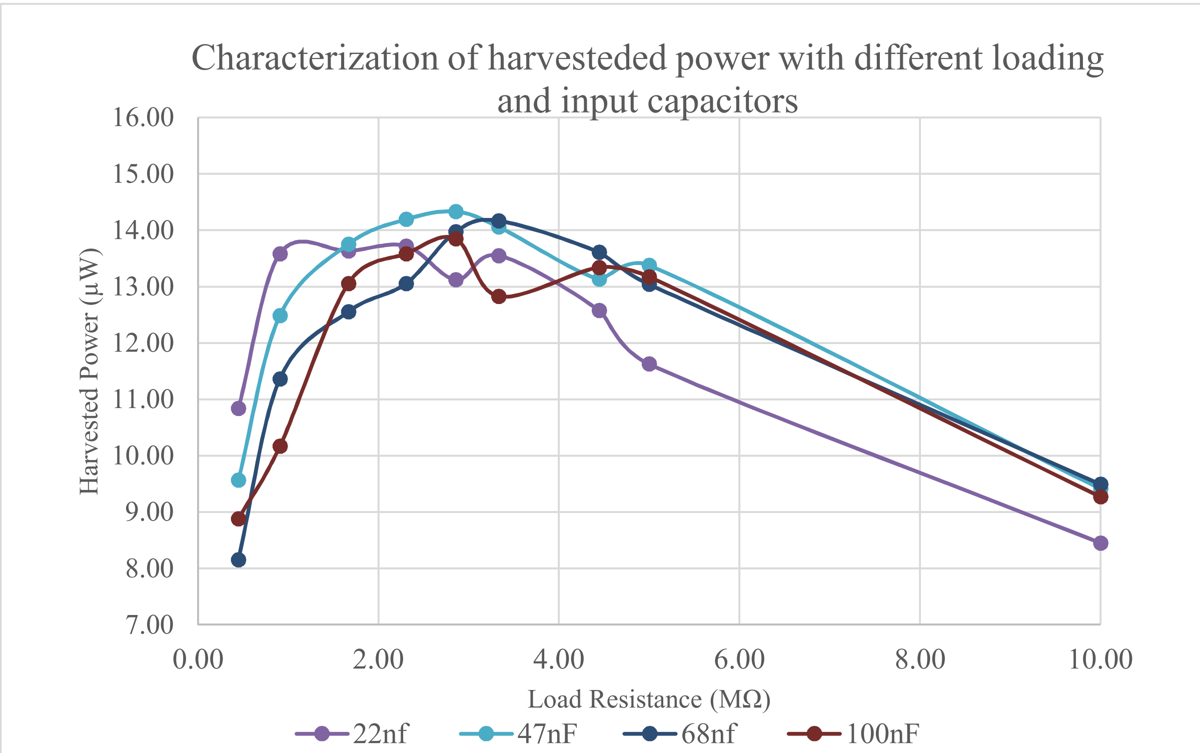

Fig. 3: Output power of the harvester for different input capacitance values with varying loads.

It can be noted that the output power varies against loading of the harvester with a slight variation due to the input capacitance value. This observation is important to consider when designing the PMS to ensure operation near the MPP, regardless of the input capacitance value. Hence, it is possible to track the MPP of the harvester, if one can track and change the input resistance of the buck converter as seen by the harvester. That happens by controlling the input voltage of the buck converter.

From Fig. 3, it can be interpreted that the input capacitance value has a negligible effect on the system design. However, if we consider energy as the judgement criterion to select the input capacitor, the picture will be different. That is due to the fact that a smaller capacitor will charge faster, improving the system performance during high frequency excitation of the harvester, such as the case where the harvester is mounted to a motor or wind turbine blades, similar to the Fig. 3 test conditions. Such use cases with continuous excitation will prefer a smaller input capacitance value as the input voltage does not drop quickly because of the nature of the use case. For other use cases where there is only a single excitation event, such as a smart floor, a bigger input capacitor will be more beneficial as it will hold the charge for longer time periods and results in more energy output. Another figure showing the output power vs input capacitor value could not be obtained due to the lack of a systematic single excitation source.

Maximum Power Point Tracking

There are several well-known methods to track the MPP of a system, such as perturb and observe, incremental conductance or the constant voltage method [28]. The problem with these methods is that they all need to measure the instantaneous voltage or current levels. Additionally a microcontroller is needed to perform calculations using the measured values to ensure MPPT. But these continuous measurements additional to the microcontroller need a lot of energy, which has to be provided, in case of a standalone version, by the system. It is questionable if the improvement through these calculations outweigh the additional energy consumption in a standalone system. Thus a standalone energy harvesting system stands to benefit if the MPPT implementation only relies on low energy components.

It was shown in the previous paragraph that the local maximum power point is highly dependent on the load resistance seen by the harvester (the input resistance of the buck converter), while the input capacitor has hardly any effect on that point. This means that the system should continue charging the input capacitor until that capacitor´s voltage reaches the ideal level in relation to the input impedance of the converter and the converter´s load resistance. It is possible to increase the output power of the harvester by varying the enabling voltage level of the converter. This is done using a low power comparator, which enables the converter at a certain input voltage level to increase the energy output of the converter compared to the system without the MPPT. The comparator was tuned to generate the enabling signal for the converter, when the MPP voltage is reached. Also, a hysteresis for the comparator was added to ensure the enable signal stays high as long as the input voltage is high enough for the converter to work. To verify this implementation, several measurements were taken using different PCBs. The input and output capacitors were varied to show how these values affected the energy output.

Experimental Results

To demonstrate the previously described concepts, different prototypes were built and tested. High impedance probes (>10MΩ) were used to collect all the data due to the low power nature of the application. The PMS was powered only by a PENG to realize a standalone use case. To prove the effectiveness of the PMS, all the measurements were collected with a single deformation event, not through continuous excitation which inherently generates more energy. The output voltage waveform of the PMS was processed using the CSV measurement provided by the oscilloscope. These data points were used to calculate the RMS voltage level of the output signal and then the output power and energy. This was done at different output voltage levels and different input and output capacitance values. To demonstrate the effectiveness of the presented MPPT concept, the MPPT block was disabled and enabled and the harvested output energy was compared.

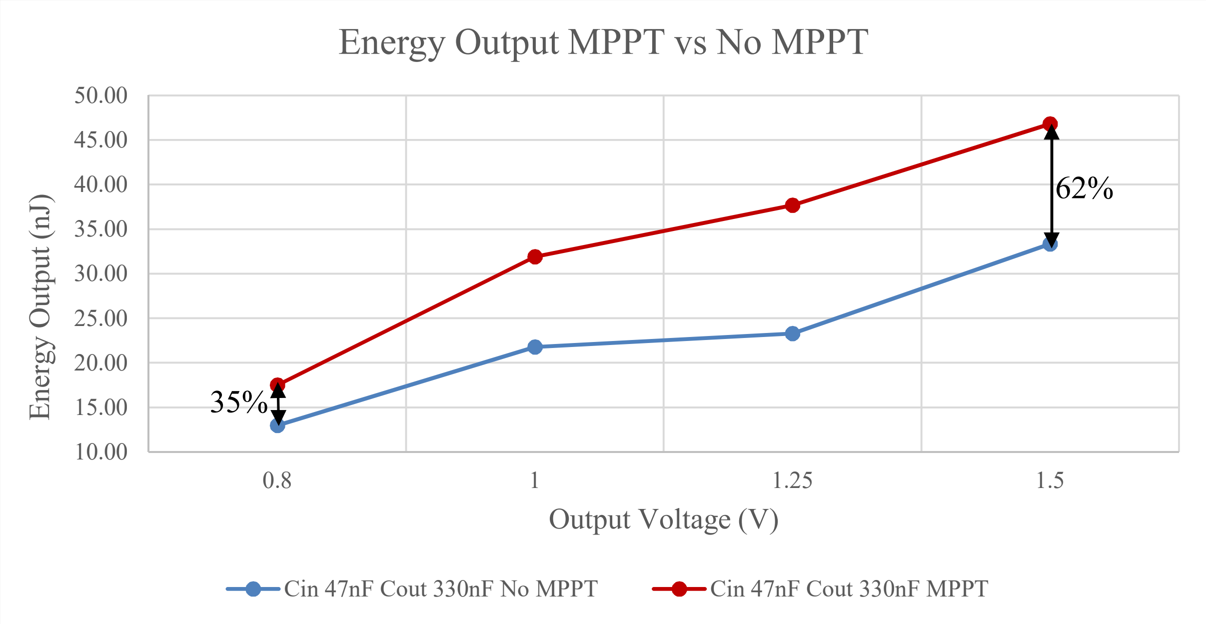

Fig. 4: Harvested energy comparison with and without MPPT with 47nF input capacitor and 330nF output capacitor.

Figure 4 shows a comparison between the harvested energy with and without the MPPT block using a 47nF input capacitor and a 330nF output capacitor. The MPPT technique presented in this work results in an improvement of the harvested energy between 35-62% with a single deformation event.

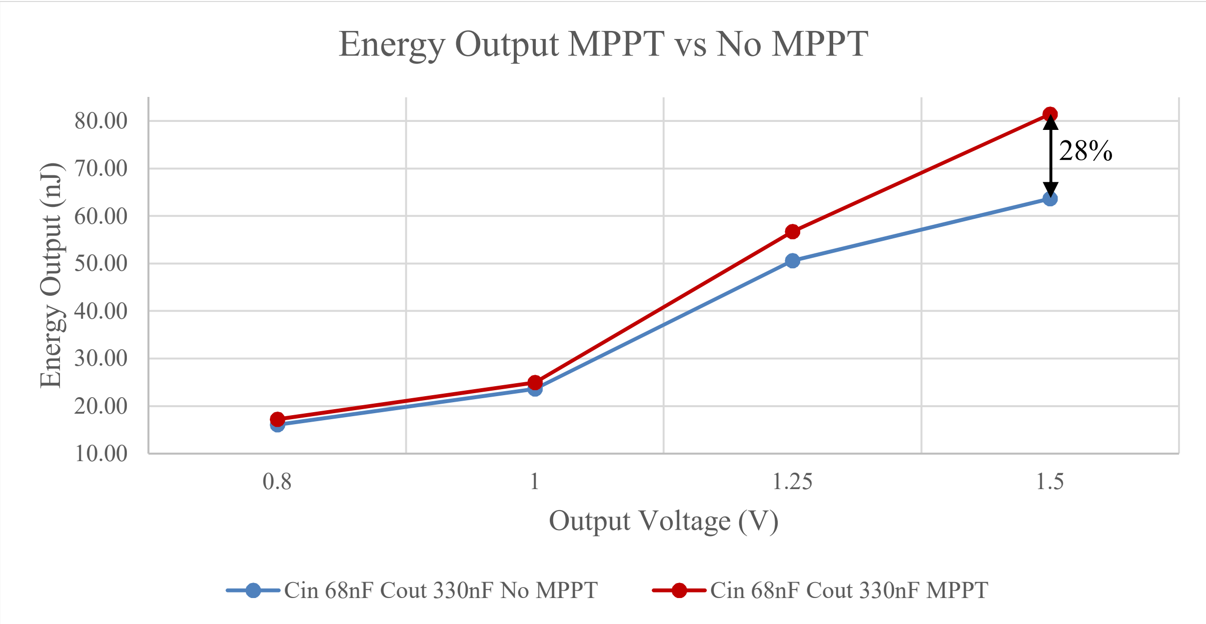

Fig. 5: Harvested energy comparison with and without MPPT with 68nF input capacitor and 330nF output capacitor.

The same test was repeated with a 68nF input capacitor and a 330nF output capacitor. The PMS was able to harvest more energy as explained earlier. The MPPT even improved the harvested energy by up to 28% at 1.5V. The general improvement of the output energy makes sense since the larger input capacitor can store more charges and needs longer to charge up than the smaller input capacitor. The size of the input capacitor does have limitations. To further increase the output energy, a 100nF input capacitor was used, but the circuit would not function properly because the input voltage of the comparator could not reach a level, where it would enable the converter. This showed, that 68nF is the optimal input capacitance value for the PMS evaluated for these measurements.

In order to optimize the output capacitor value, the output capacitor was changed between 100nF and 470nF and the previous test was repeated. The conclusion was that small output capacitance values results in a larger overshoots and had negative impact on the PFM stability while larger output capacitance values slow down the output voltage, reducing the useful time where the load can benefit from the output voltage value. Therefore, 330nF was used as an optimal capacitance value for the presented PMS.

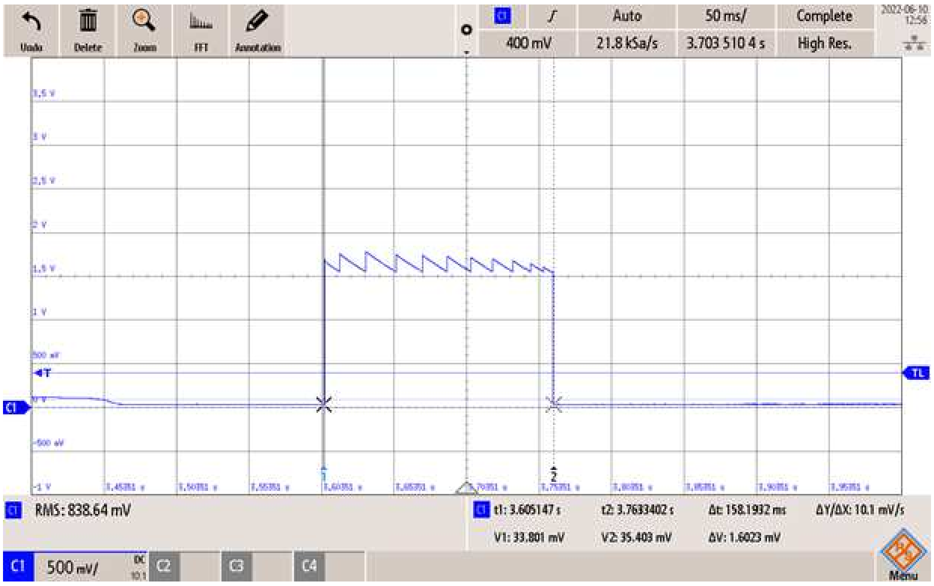

Fig. 6: Output voltage behavior of the standalone use case, with a nominal value of 1.5V.

Figure 6 shows the regulated output voltage with the optimal input and output capacitor values at 1.5V with a single deformation. It can be noted that the PFM controller regulated the output voltage at the valley point and the output capacitor keeps the output voltage ripples at an acceptable amplitude. The voltage waveform is regulated for 160mSec which is enough for sensing and transmission in many IoT systems [29].

The harvested energy was also measured versus the output load resistance and a comparison between the harvested energy with and without MPPT is shown in Fig. 7. It is worth mentioning that these results were collected with the optimal input and output capacitor values, as determined before. It is clearly visible that the system with MPPT improves the energy output of the converter while maintaining almost exactly the same output power. This can be achieved due to the fact that the PENG produces the most energy when the load applied to it matches the internal impedance of the harvester. By manipulating the input voltage of the converter and enabling it at a later point one can artificially generate a different load resistance seen by the harvester to optimize the energy conversion. This lead to an improvement of up to 44% compared to the system without the MPPT.

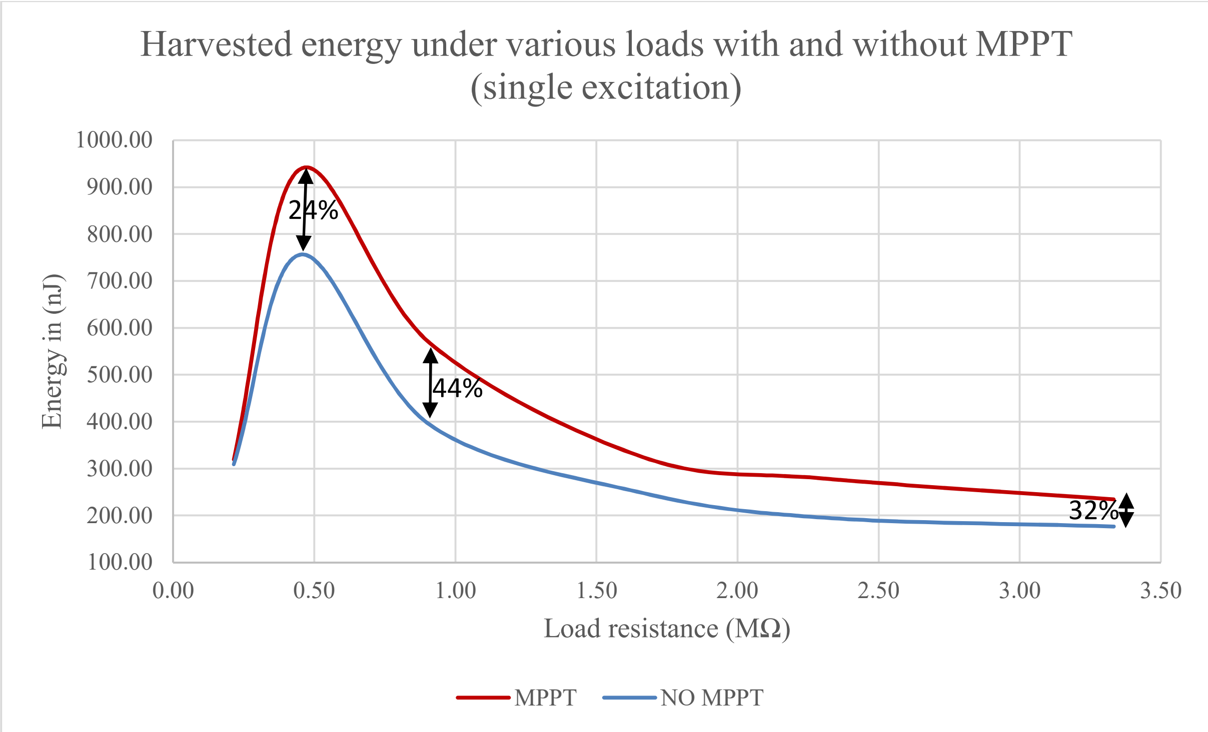

Fig. 7: Energy characteristics for 1.5V output versus different load resistances.

Figure 8 shows how the converter is activated after a short startup phase, when the input voltage reaches 3V (the predetermined MPPT value).The input voltage to the comparator is measured through the voltage divider, and when the 0.2V reference is met, the converter is enabled. The input voltage of the converter decreases as the converter is transferring energy to the output.

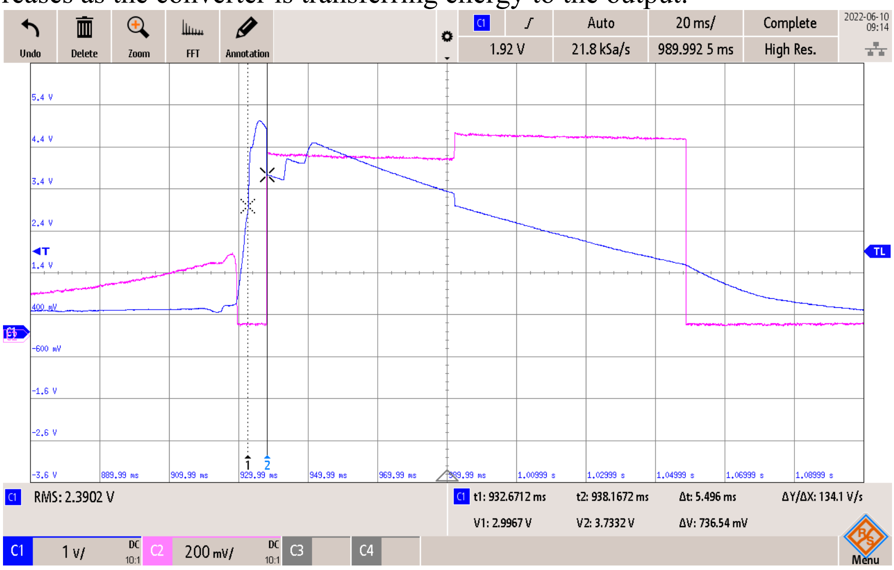

Fig. 8: Input voltage signal (blue), regulated output voltage (pink).

The PENG was also developed to capture, accumulate and store energy. The prototype is capable of efficiently managing harvested energy to charge the battery powered system. A low-power SMD battery (TDK- Ceracharge) is used for the design, requiring an input voltage between 1.5V-1.6V which can be delivered by the regulated output of the buck converter. The battery together with a blocking diode, to prevent self-discharge, were connected in parallel to the power management system (PMS). Fig. 9 shows a measurement of the voltage across a resistor connected in series with the battery, to show the behavior of the charging current entering the battery.

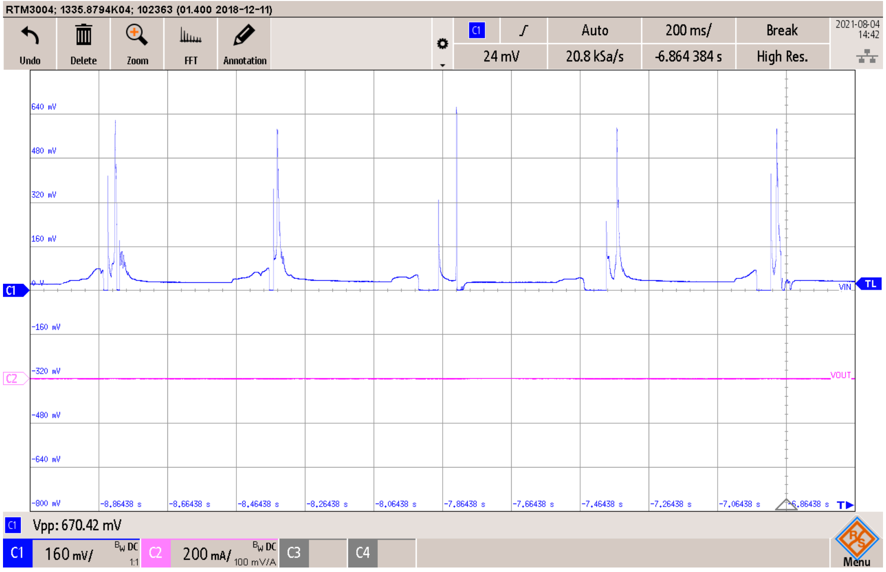

Fig. 9: Energy stored in a battery.

Conclusions

In this paper, we have presented an energy harvesting system that is capable of delivering a peak output energy of up to 900nJ with a single deformation. The presented MPPT solution improves the harvested output energy by up to 44% while providing a regulated output voltage. The operation of the PMS covered two different use cases, both as a standalone application and with energy storage. Insights about selection of the optimal input and output capacitances were shown and implemented in this paper.

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