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A Self-Sustained Microcontroller Regulated Energy Extraction Network for Piezoelectric Energy Harvesters

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Summary:
The presented energy extraction network regulates the output voltage of a rectifier in order to meet the point of maximum power extraction. This point depends on the mechanical excitation of a piezoelectric energy harvester. The obtained results are compared to an unregulated approach. Though the proposed solution requires a higher supply current, the overall power output remained comparable. Additionally, the option of managing the harvested energy was gained. This leads to a promising feature for various self-sustained applications.

Keywords: Piezoelectricity, Internet of Things, Asset-Tracking, Energy-Autarchic, Low-Power and Harvesting

Background, Motivation and Objective

Wireless sensor systems are widely used in industrial, consumer and medical applications. Most of those sensor systems are powered by batteries, which have to be replaced, recharged and disposed after their lifetime. This results in operational expenses and is harmful for the environment. Consequently, there is a great demand for self-sustained systems.

The key-technology for the development of such systems is energy harvesting. In [1], a cantilever based piezoelectric energy harvester (PEH) was used to convert the mechanical power from the movement of an asset into electrical power. This obtained electrical energy was used to send radio-transmissions that allow to track an asset. The piezoelectric principle was chosen for several reasons: Firstly, it delivers excellent conversion rates from mechanical into electrical power [2]. Secondly, it can be implemented in simple and scalable structures. And finally, it can not only serve as a source of energy, but also as a sensor that detects the movement of the asset.

The piezoelectric conversion is based on the coupling between the mechanical and the electrical domain of the harvesting structure. Therefore, it naturally inherits a resonant behavior, which acquires the most ambient power for sinusoidal excitation at its resonance frequency. Consequently, the eigen frequency of the harvesting structure must coincide with the most powerful spectral component of the excitation for maximum power output.

Additionally, a proper electrical network is needed to extract and provide the harvested energy. A lot effort has been made to design synchronized energy extraction circuits for PEHs (SSHI, SSHC, SECE). However, it has been shown in [3] that such energy extraction networks (EEN) do not perform better than a conventional rectifier for PEHs with strong coupling which are excited referenced to acceleration. Nonetheless, the full-bridge rectifier also has drawbacks. The amount of extractable energy depends on the ratio of the voltage V_{C1} of the storage capacitor to the open-circuit voltage $V_{PEH,OC}$ of the PEH, because the energy extraction is based on a capacitive-capacitive discharge.

In [1], a two-stage EEN, which regulates the voltage V_{C1} to a predefined value, was proposed. If the excitation scenario deviated from the expected one, a decrease in the amount of extractable power was observed. To overcome this undesired behavior, we introduce a completely self-sustained, microcontroller regulated EEN for PEH. The proposed EEN regulates V_{C1} to meet the point of maximum extractable power for each excitation scenario dynamically.

Energy Extraction Network

The EEN is displayed in Fig. 1. The top part shows the power path and the bottom part describes the generation of the supply voltage V_{DD} for the microcontroller (MCU), which regulates

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the network. The power path consists of a full-bridge rectifier connected to the input capacitance C_1 of a flyback converter. The switching signal V_G is deducted from a comparison of the input voltage V_{C1} to the internal voltage V_{DAC} of the MCU. By varying V_{DAC}, V_{C1} is adjusted to meet the maximum power-point. At this point, V_{C1} is half of the open circuit voltage of the PEH $V_{PEH,OC}$.

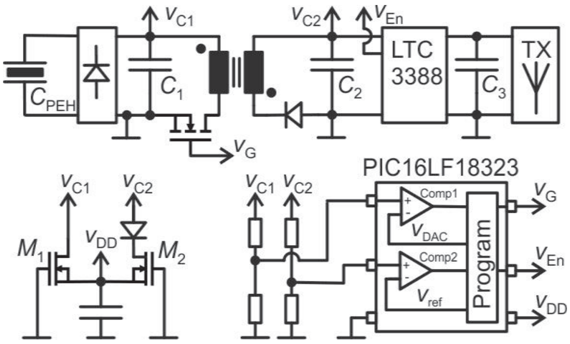

Fig. 1. Schematic of the proposed EEN.

Since $V_{PEH,OC}$ is not available to measure it directly, it is calculated in the software of the MCU according to

$$V_{PEH,OC} = \frac{n_S}{t_{eval}} \frac{1}{2f_r} \frac{C_{PEH} + C_1}{C_{PEH}} V_H + V_{C1,pre} . \quad (1)$$

Thereby, n_s is the number of switching events of the signal V_G in the evaluation time t_{eval}. The capacitance and the resonance frequency of the used PEH are given by C_{PEH} and f_r, respectively. Furthermore, the hysteresis voltage V_H of comparator 1 and the DAC-voltage $V_{C1,pre}$ of the previous step are necessary. Needless to say, all of those values can be easily adjusted according to the used PEH.

Peripheral units of the MCU like counters, timers and internal voltages can be used in its sleep mode and are activated solely on demand. So, the MCU only has to wake up to evaluate (1) and check if there is enough energy in the storage capacitance C_2 to activate the buck converter LTC3388 and the application. This results in a low average current consumption of 20 μA at 2.2 V, which accounts for less than 8 % of the harvested power for excitation scenarios with RMS($V_{PEH,OC}$) > 30 V.

Results and Discussion

In order to test the capabilities of the proposed network, we excited the PEH on a vibration test system with respect to acceleration, applying noise signals with different amplitudes. This simulates different excitation scenarios with different $V_{PEH,OC}$. For each of those, the harvested mean output power was measured. We compare the proposed regulated approach with the previous analog solution from [1]. The measurements were obtained with completely self-sustained EENs and are depicted in Fig. 2.

As the results revealed, the overall power output for the regulated EEN is comparable to the power output for the constant V_{C1} approach in [1]. For excitation scenarios that produce a $V_{PEH,OC}$ < 30 V, the proposed solution is inferior to the approach with constant V_{C1}. This is so because the previous analog solution requires less current to supply itself (4μA) since it does not need a MCU to function.

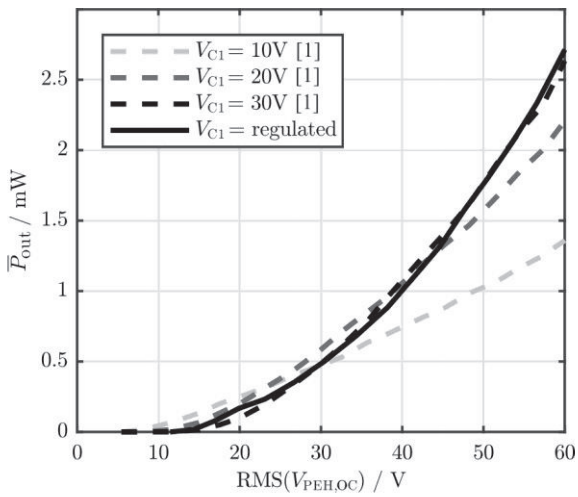

Fig. 2. Comparison of the mean output power $\overline{P}_{out}$ for different excitation scenarios ($V_{PEH,OC}$). Dashed lines: output power for analog solution [1]. Solid line: output power for regulated V_{C1}.

For use-cases that provide higher $V_{PEH,OC}$, the proposed regulated EEN adapts V_{C1} automatically and delivers a higher power output compared to low predefined values V_{C1}.

The proposed EEN delivers another major advantage for the asset-tracking application: While the previous approach always sent a transmission, when there was just enough energy stored to do so, the novel approach can manage the harvested energy. This gives the possibility to gather the energy when the asset is moving and to send the transmission for position update after the movement of the asset.

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