Combined Power Extraction with Adaptive Power Management Module for Increased Piezoelectric Energy Harvesting

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Abstract—**This paper presents a combined power extraction with adaptive power management module (PMM) for increased piezoelectric energy harvesting. The PMM is adaptive towards variations in the amplitude and frequency of vibration subjected by the strain energy harvester () and different connected electrical loads, and is able to harvest power at maximum or near maximum power point (M/NPP) of the SEH. Therefore, the combined circuit allows up to 156 % more power to be harvested from the SEH. This feature is especially crucial under low frequency and low vibration amplitude conditions to greatly improve the power generated from the SEH which is usually very low under such low vibration scenario.**

Keywords—adaptive power management; piezoelectric energy harvesting; power extraction; strain energy harvester

I. INTRODUCTION

Wireless sensor nodes (WSNs) are becoming more and more ubiquitous in many applications due to their advantages such as ease of installation across a wide area and hard-to-reach areas over wired sensors. The widespread of WSNs urges for new energy sources to power up the WSNs which are mostly run on batteries. This is because batteries have limited energy capacity and thus require regular replacement which can be very costly and tedious . Energy harvesting has therefore received a flurry of research interest as an alternative or supplementary energy source for WSNs [2].

Vibration-based energy harvesting is particularly attractive because vibration is abundant, where it can occur either naturally from the environment or induced by means of other sources such as biomotion or machinery [3]. Piezoelectric energy harvesters (PEHs) are commonly used to scavenge vibration energy due to their self-contained power generation capability, simple structure, and high energy density [4]. However, power available from PEHs can be intermittent since the vibration is spatially and temporally variable. Also, WSNs draw different amount of current during different operational modes, which effectively make it a dynamic load. Therefore, a power management module (PMM) which is adaptive to both the variations in the PEHs and WSNs is required to realize an energy self-sufficient WSNs powered by PEHs. Since the energy generated by PEHs is usually lower than the energy demanded by WSN, energy will have to be accumulated in an energy storage device such as capacitor and released to the WSN once sufficient. This means operation of an energy harvesting-based WNS is periodical.

Extracting more power from the PEHs is always demanding in order to quickly charge up the energy storage capacitor so that the WSNs can be turned on as soon as possible to perform sensing tasks. The most common power extraction method is the nonlinear technique which uses switches and most of the time, inductors to change the voltage waveform from the PEHs [5-7]. Voltages from PEHs are increased using the nonlinear technique and therefore the power increases as well.

Many power extraction methods have been proposed but most of them were validated using cantilever type PEHs which are operating at their resonance frequencies and vibrate freely at one end of the beam which have a mass on them [e.g., 6]. However, in some applications where frequency is at non-resonance and low, and weight is a concern [8], patch type PEHs such as macro fibre composite (MFC) is a more suitable candidate. The MFC is bonded on a host structure as a SEH that converts the mechanical strain energy from the host structure into electrical energy, usually at non-resonance. Therefore, an investigation of power extraction on SEH is necessary as well.

This paper herein presents a combined power extraction with an adaptive PMM circuit for increased energy harvesting. The circuit was implemented using full analogue components with low power consumption to ensure that the circuit can be entirely powered up using SEH especially under low vibrational conditions where the energy harvested is low as well. Therefore, the focus here is to apply low frequencies from 2 to 10 Hz and low strain loadings from 100 to 300 $\mu\varepsilon$ onto the SEH. Up to 156 % more power can be harvested using this PMM compared with PMM without power extraction capability.

II. System Description

A. Adaptive Power Management Module

An adaptive PMM was reported at IEEE Sensors 2015 [9] where the PMM can harvest energy from a SEH at its maximum power point (MPP) regardless of vibrational frequencies or strain levels exerted onto the SEH or electrical load connected to the PMM. The exactly same circuit is used here to harvest energy from the SEH and power up the WSN.

A rectifier is used to convert AC voltage from the SEH into DC voltage which is then fed into the PMM. The PMM finds and harvest energy from the SEH at its MPP. Voltage from the SEH is usually high. Therefore, PMM steps down the high voltage to a well-regulated 3.15 V DC voltage which charges up a storage capacitor. Once the storage capacitor is charged up to 3.15 V, the energy aware interface (EAI) releases the energy from the capacitor to power up the WSN. Voltage across the capacitor then decreases as energy is drawn out. When the voltage across the capacitor drops to a low threshold, the EAI turns off the WSN to allow the capacitor to be recharged. This cycle repeats as long as there is vibration.

The WSN was implemented using Jennic JN5148 microcontroller (MCU) and three sensors including a humidity sensor, a temperature sensor, and an accelerometer. JN5148 is a low power MCU which has a 2.4 GHz IEEE 802.15.4 compliant transceiver to communicate using ZigBee protocol.

B. Power Extraction Circuit

The power extraction circuit sits in between the SEH and the rectifier as shown in Fig. 1. The power extraction methods employed are implemented by the switch-only rectifier [7] and the parallel synchronized switch harvesting on inductor (P-SSHI) by adding an inductor in this paper. The circuits were implemented using full analogue components [10]. This power extraction circuit is load dependent, meaning that maximum power transfer occurs only when it is connected to an optimal load. In order to overcome the load dependent feature, , a combined power extraction with the adaptive PMM discussed above were implemented in one circuit and provides a practical solution for real world applications with power extraction capability at MPP of the SEH. To the authors' best knowledge, this is the first time that a switch-only rectifier or P-SSHI circuit is adopted into a full analogue PMM with MPP finding capability and powered by a SEH.

III. Experiment

To determine the improvement in terms of power harvested provided by the power extraction circuit, the three different combined power extraction with the adaptive PMM circuits were implemented to harvest energy from the SEH which was subjected to strain loadings of 100, 200, and 300 με at 2, 4, 6, 8, and 10 Hz to power a WSN., where the power extraction circuits are (1)switch-only rectifier, (2) P-SSHI with 100 μH, and (3) P-SSHI with 1 mH. The following comparisons were made with and with power extractions:

(1) The time required to charge up the storage capacitor from 0 to 3.15 V and power up the WSN when the SEH is subjected to a peak-to-peak strain loading of 300 με at 10 Hz.

(2) The input powers for the chosen combined circuit when the SEH was subjected to strain loadings of 100, 200, and 300 με at 2, 4, 6, 8, and 10 Hz to power a WSN.

IV. Results and Discussions

Results from the comparison (1) are shown in Fig. 2. Adding inductor in the power extraction circuit will get more power from the SEH. Therefore, the storage capacitor can be charged up to 3.15 V and the WSN was turned on in the shortest time when an inductor of 1 mH was used. This is followed by the power extraction circuit using inductor of 100 μH, switch-only rectifier, and finally without any power extraction.

These results agree with previously reported findings where larger inductance provides more power increment [7]. However, the increment is not as drastic as in the case of using a cantilever-type PEH. For example, more than 200 % of improvement in terms of power harvested was reported in [7] when an 820 μH inductor is used, if compared with switch-only rectifier. Theoretical analyses reported in the past show that the power increment is related to the mechanical displacement of the cantilever-type PEH and structural stiffness [5]. Given that the SEH does not vibrate freely as the cantilever-type PEH, the SEH has limited displacement and effectively higher damping which causes less amount of power to be extracted.

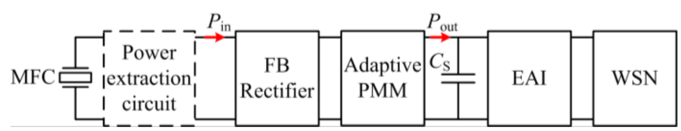

Fig. 1. Block diagram of the circuit with a combined power extraction with MPP finding circuit

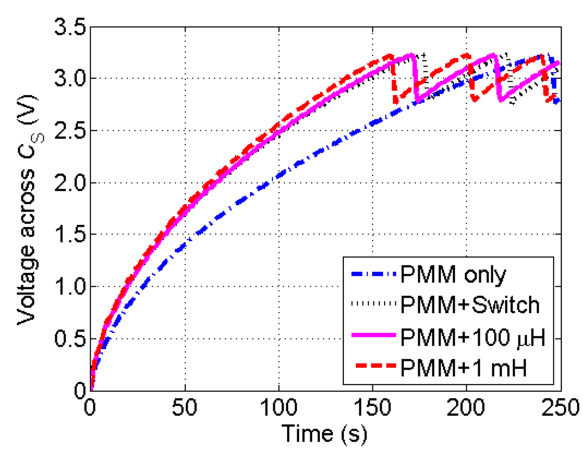

Fig. 2. Comparisons of the different power extraction configuration circuits in the time required to charge up a 22 mF storage capacitor C_S when the SEH is subjected to a peak-to-peak strain loading of 300 με at 10 Hz

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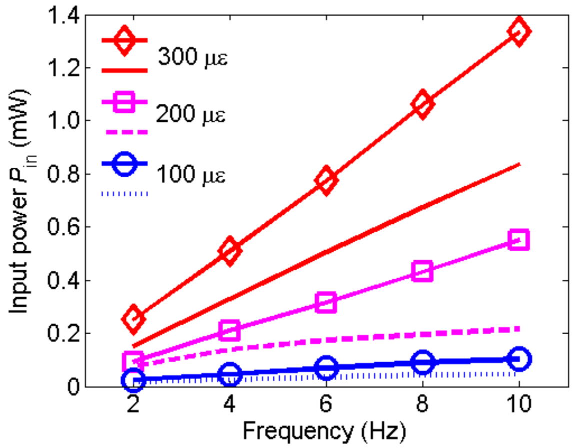

Fig. 3. Comparisons of the circuits with (markers) and without (lines) power extraction in the input power to the PMM when the SEH is subjected to peak-to-peak strain loading of 100, 200, and 300 με at frequencies of 2, 4, 6, 8, and 10 Hz

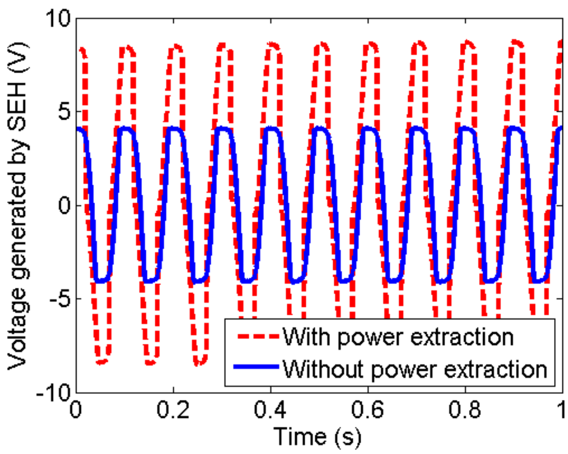

Fig. 4. Comparison of the circuits with and without power extraction in the voltage generated by the SEH under a peak-to-peak strain loading of 100 με at 10 Hz

TABLE I. POWER IMPROVEMENT AT DIFFERENT STRAIN LOADINGS

Frequency (Hz)	**Power Improvement (%)**		
	100 με	***200 με***	***300 με***
2	34.76	22.06	8.637
4	83.37	50.94	36.19
6	96.52	80.72	41.26
8	110.14	121.00	45.08
10	121.74	155.16	48.77

V. SINCE ADDING AN INDUCTOR ONLY IN THE POWER EXTRACTION CIRCUIT SLIGHTLY IMPROVES THE AMOUNT OF EXTRACTED POWER AND IT ALSO ADDS WEIGHT AND OCCUPIES MORE SPACES, THE SWITCH-ONLY RECTIFIER IS CHOSEN IN THE SECOND COMPARISON. FIG. 3 COMPARES THE INPUT POWER INTO THE PMM WITH AND WITHOUT POWER EXTRACTION CIRCUIT AT DIFFERENT STRAIN LOADINGS AND FREQUENCIES. WITH POWER EXTRACTION CIRCUIT, MORE POWER CAN BE HARVESTED.

VI. CONCLUSION

A combined power extraction with an adaptive PMM circuit for increased piezoelectric energy harvestinghas been presented. Up to 156 % more power can be harvested and tyhis is especially useful in enabling energy harvesting powered WSN to be able to operate under low vibrational conditions where the power generated by the SEH is low as well. This feature is important especially in the pursuit of a truly energy self-sufficient system.

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