Triple Hybrid Energy Harvesting Interface Electronics

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Abstract. This study presents a novel triple hybrid system that combines simultaneously generated power from thermoelectric (TE), vibration-based electromagnetic (EM) and piezoelectric (PZT) harvesters for a relatively high power supply capability. In the proposed solution each harvesting source utilizes a distinct power management circuit that generates a DC voltage suitable for combining the three parallel supplies. The circuits are designed and implemented in 180 nm standard CMOS technology, and are terminated with a schottky diode to avoid reverse current flow. The harvested AC signal from the EM harvester is rectified with a self-powered AC-DC doubler, which utilizes active diode structures to minimize the forward-bias voltage drop. The PZT interface electronics utilizes a negative voltage converter as the first stage, followed by synchronous power extraction and DC-to-DC conversion through internal switches, and an external inductor. The ultra-low voltage DC power harvested by the TE generator is stepped up through a charge-pump driven by an LC oscillator with fully-integrated center-tapped differential inductors. Test results indicate that hybrid energy harvesting circuit provides more than 1 V output for load resistances higher than 100 kΩ (10 μW) where the stand-alone harvesting circuits are not able to reach 1 V output. This is the first hybrid harvester circuit that simultaneously extracts energy from three independent sources, and delivers a single DC output.

1. Introduction

Utilizing scavenged energy from environment becomes viable with the decreasing power demand of the new generation integrated circuits. Most common ambient sources are solar, thermal, vibration and RF energy where each micro-harvester by itself is typically limited in power generation capacity, and output voltage level. However, hybrid systems that effectively harvest multiple sources have potential to address this problem [1-3].

Several attempts have been reported in literature to build hybrid energy harvesters. Hybrid system presented in [4] combines RF and vibration based piezoelectric harvester structures to continuously power up a wireless sensor by switching between the two harvester outputs. Another hybrid structure, which utilizes TE and photovoltaic harvesters in order to generate individual power sources for multi-sensor wireless microsystem is described in [5]. The implemented system uses a microcontroller and arrange which power source to supply different sensors at the microsystem. These structures are

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useful when scavenged power from either harvester is sufficient to maintain the load power by itself, but do not couple multiple harvester outputs to increase the total output power.

In this paper, a triple hybrid structure is presented, which simultaneously combines scavenged power from TE, vibration based EM, and PZT harvesters to support higher loads at the output. The hybrid structure utilizes a power management circuit to generate a single DC power source from three different ambient sources. The AC power generated by EM and PZT harvesters are converted into DC while the low level DC output of the TE generator is boosted up to similar voltage level. The interface circuits have been designed, fabricated at UMC 180nm CMOS technology, and are connected in parallel with schottky diodes, before system validation. The organization of this paper is as follows: The proposed circuit topologies have been briefly described in Section II. Section III presents the test results from the triple hybrid structure. Finally, conclusions are summarized in Section IV.

2. Interface Circuits

Figure 1 shows the proposed triple hybrid energy harvesting system. Each interface circuit, designed and implemented in 180nm standard CMOS technology, contributes in parallel to power management to combine the harvested signals from EM, PZT and TE generators into a similar DC level. Each harvester sub-system is terminated with a schottky diode to avoid reverse current flow. The harvested AC signal from the EM harvester is rectified with a self-powered AC-DC doubler, which utilizes active diode structures to minimize the forward-bias voltage drop. The PZT interface electronics utilizes a negative voltage converter as the first stage to use full cycle of the input signal. The power extraction circuit also performs the DC-to-DC power conversion through a set of power switches and an external inductor. The ultra-low voltage DC power harvested by the TE generator is stepped-up by a charge-pump circuit driven by LC oscillator with fully-integrated centre-tapped differential inductors. The oscillator replaces digital oscillators with a low cost voltage-doubling LC tank implemented with on-chip inductors, eliminates large CMOS buffers, and thus provides high step-up ratio through reduced losses. Detailed description of TE interface electronics was given in [6] where details of EM and PZT interfaces were given below.

2.1. Rectifying Electronics for EM Harvester

EM harvesters are good candidates for low frequency ambient vibrations due to their low resonant frequency characteristics. The proposed system utilizes a self-powered AC/DC doubler as shown in Figure 2 which is the modified version of the rectifier presented in [7]. Rectification of the signal is obtained by active diodes, which is composed of a comparator and a PMOS switch. The active diodes enable low forward voltage drop and high current drive; however they require a DC supply to operate. In the proposed structure, positive and negative supplies of the comparators are provided internally by passive AC/DC positive quadrupler and passive AC/DC negative doubler, which are constructed with diode connected PMOS transistors. The input signal of these passive circuits are also maintained from the same harvesting source. Therefore the circuit operates without additional sources.

Operation principle of the circuit is as follows: When the input voltage is negative and V_x potential is lower than GND, the right sided comparator turns the transistor ON and the storage capacitor between the input and V_x node is charged up to positive peak voltage of the input. When V_x goes above ground potential, the switch is turned OFF, and a positive charge is stored on the capacitor. Similarly, when the input is positive and the V_x potential is above output voltage V_{rect}, left sided switch is turned ON, and output storage capacitor is charged. When V_{rect} falls below V_x, the switch is turned OFF, and a doubled voltage is stored on the output storage capacitor.

2.2. PZT Interface Electronics

The proposed hybrid system includes a PZT harvester subsystem, which effectively harvests high frequency vibrations. Therefore, both low and high frequency ambient vibration are captured by the system. The implemented electronic circuit for piezoelectric energy harvester is illustrated in Figure 3. In this circuit, the power extraction is realized through a set of power switches and an external inductor. Switching on the external inductor between piezoelectric clamped capacitance and the output buffer capacitance, based on Synchronous Electric Charge extraction (SECE) technique, enables boosting extracted power and transferring of the generated charge to the output capacitor [8].

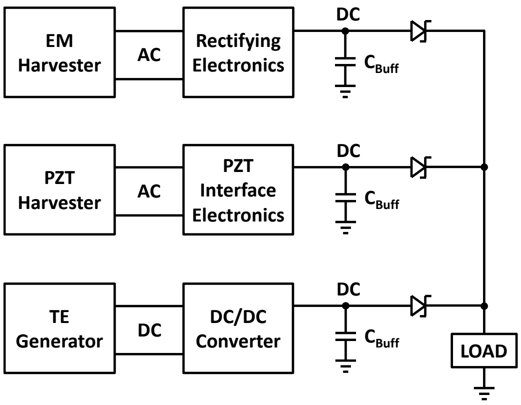


Figure 1. Triple hybrid energy harvester structure.

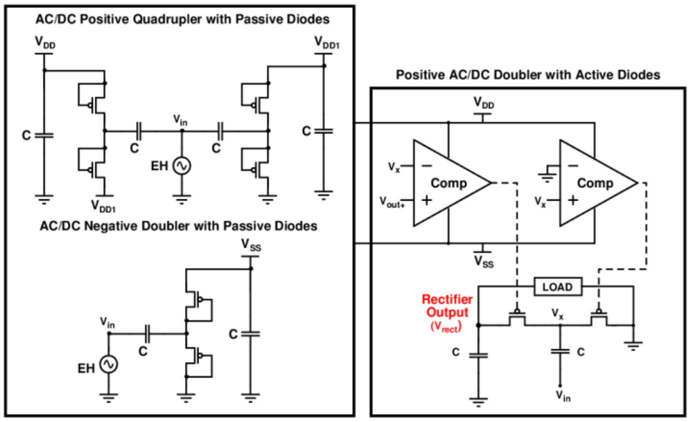
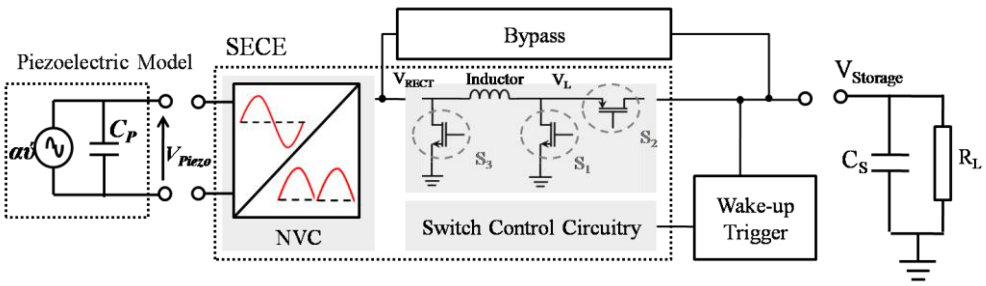


Figure 2. Self-powered rectifying electronics for low voltage EM harvester.

Initially the AC voltage generated on piezoelectric harvester is converted to positive signal through negative voltage converter (NVC). The power extraction is achieved in three phases by SECE circuit. In the first phase, all switches are turned OFF and the piezoelectric harvester vibrates in open circuit condition. The second phase is initiated by turning ON S_1 at maxima of the piezoelectric voltage. The established resonant circuit between piezoelectric clamped capacitor and the inductor transfers energy stored on the piezoelectric capacitor to the inductor. The third phase starts when piezoelectric capacitor voltage reaches to zero. At this moment, S_1 is turned OFF, S_2 and S_3 switches are ON, and the stored energy on the inductor is transferred to the storage buffer capacitance, C_S. This phase stays active until the inductor current reaches zero. After this point, a new energy transfer cycle is initiated by turning all switches OFF. High power efficiency is achieved for a wide range of output voltage by decreasing power losses in control switch circuitry and switch drivers.



(a) (b) (c)

Figure 3. Schematic of self-powered SECE harvester: (a) piezoelectric model (b) implementation of SECE (c) storage capacitance and load.

3. Test Results and Discussion

Figure 4 depicts the die micrographs of the implemented CMOS harvester chips. EM rectifying electronics is excited with 5 Hz and 1.1 $V_{peak\text{-}to\text{-}peak}$ input during validation, PZT interface electronics has input signal with 69 Hz and 3 V open-circuit voltage where both sources can be generated with low level vibrations (<1g). TE interface electronics has 0.18 V input voltage which can be easily obtained with typical TE harvesters. Figure 5 shows variation of output voltage and power of the hybrid system and stand-alone interface electronics with respect to the load resistance. Although the stand-alone harvesting circuits are not able to reach 1 V output, hybrid system provides more than 1 V output for load resistances higher than 100 kΩ. Output power of the hybrid system is higher than stand-alone system outputs, which demonstrates the benefit of combining multiple sources at a single output. Although sum of power generated at the output of each interface is higher than total hybrid power the forward voltage drop and leakage currents at the schottky diodes leads to power losses.

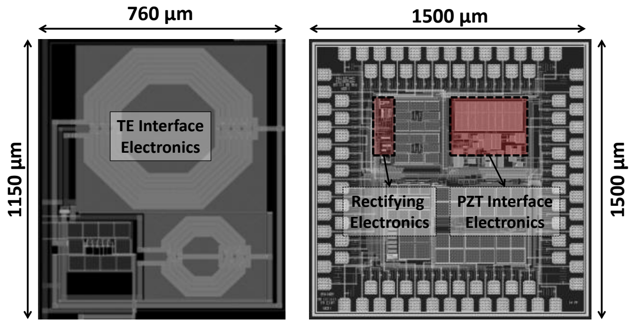


Figure 4. Die micrograph of the hybrid interface electronics in UMC 180nm CMOS technology.

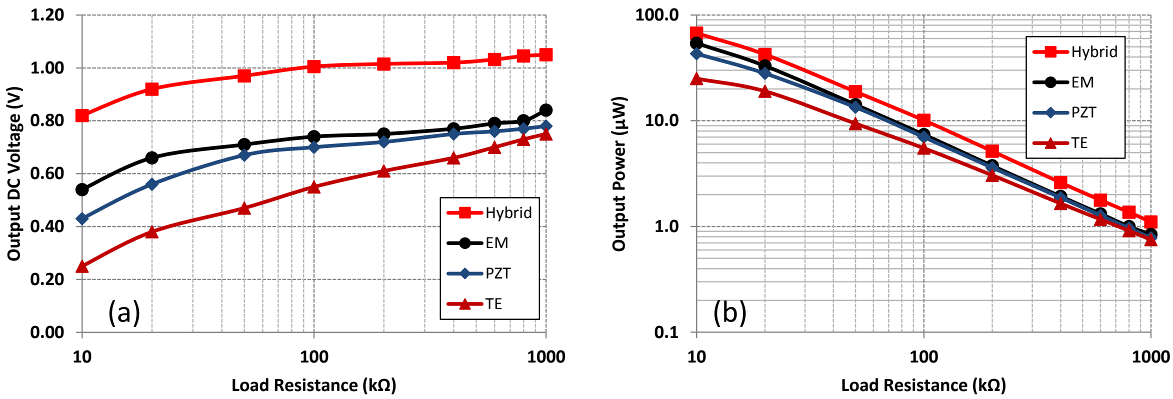


Figure 5. Variation of the (a) output voltage and (b) output power of the hybrid and stand-alone energy harvesting circuits with respect to load resistance.

4. Conclusion

A triple hybrid energy harvesting system that combines TE, vibration based EM and PZT harvester outputs at a single load is presented in this paper. The low frequency ambient vibrations are harvested by the EM harvester, and are rectified by a self-powered autonomous rectifier. The high frequency ambient vibrations are scavenged by PZT harvester, and converted into DC with a self-powered SECE interface. In addition to vibration sources, DC power scavenged from thermal energy is boosted and connected in parallel to other sources. Test results of the system showed that the hybrid structure was able to generate more than 1 V output for load resistances higher than 100 kΩ whereas stand-alone harvesting sources are not able to reach this voltage. The implemented structure is able to simultaneously combine harvested power from three different sources and generate enough voltage and power to drive low voltage sensors. It is expected that the efficiency of the hybrid system can be further increased in the future through the integration of the discrete components.

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