A Self-Powered Hybrid Energy Scavenging System Utilizing RF and Vibration Based Electromagnetic Harvesters

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Abstract. This study presents a novel hybrid system that combines the power generated simultaneously by a vibration-based Electromagnetic (EM) harvester and a UHF band RF harvester. The novel hybrid scavenger interface uses a power management circuit in 180 nm CMOS technology to step-up and to regulate the combined output. At the first stage of the system, the RF harvester generates positive DC output with a 7-stage threshold compensated rectifier, while the EM harvester generates negative DC output with a self-powered AC/DC negative doubler circuit. At the second stage, the generated voltages are serially added, stepped-up with an on-chip charge pump circuit, and regulated to a typical battery voltage of 3 V. Test results indicate that the hybrid operation enables generation of 9 µW at 3 V output for a wide range of input stimulations, which could not be attained with either harvesting mode by itself. Moreover, the hybrid system behaves as a typical battery, and keeps the output voltage stable at 3 V up to 18 µW of output power. The presented system is the first battery-like harvester to our knowledge that generates energy from two independent sources and regulates the output to a stable DC voltage.

1. Introduction

Energy harvesters use environmental sources such as solar, thermal, vibration and RF energy to generate electrical energy. The decreasing power demand of the new generation integrated circuits allow the use of micro-harvesters as energy sources in microsystems as an alternative to batteries. However, each micro-harvester by itself is typically limited in power generation capacity, and output voltage level. Hence, hybrid systems are of high interest to effectively harvest multiple sources while generating sufficient voltage and power levels for an increased number of applications [1], [2].

There are several attempts in literature to build hybrid energy harvesters. System presented in [3] utilizes RF and vibration based piezoelectric harvester structures to generate continuous power for a wireless sensor by switching between the two harvester outputs. Another hybrid structure, which uses RF and EM harvesters for structural health monitoring, utilizes the harvested power to generate two discrete and independent outputs, one per harvesting mode [4]. These structures are useful when enough power is scavenged from either harvester to support the load by itself, but do not provide the means to effectively couple the two harvester outputs.

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In this paper a hybrid structure is presented, which adds and boosts the simultaneously scavenged power from RF and EM harvesters to support higher loads at the output. The structure consists of a positive and a negative dual rail rectification for the AC signals scavenged from RF and EM harvesters, and a low voltage DC/DC converter to boost and stabilize the output at the desired value. The interface circuit has been designed, fabricated at UMC 180 nm CMOS technology, and validated. The organization of this paper is as follows: Section II briefly describes the proposed circuit topologies. Section III presents the obtained test results of the hybrid harvester system. Finally, conclusions are summarized in Section IV.

2. Interface Circuit Description

Figure 1 presents the block diagram of the proposed hybrid system that scavenges the low frequency (< 20Hz) vibrations and UHF RF signals, and combines them to drive higher loads. The vibrations are harvested by an in-house EM energy harvester optimized to obtain best performance at 2x2x2 cm\(^3\) of volume\[5\]. The RF harvester operates at 900 MHz frequency. The scavenged power from RF and EM modules is converted into positive and negative polarities respectively, with a common reference. Continuous current flow is therefore obtained from positive to negative terminals, and no external component is needed to combine the generated powers. The rectified low voltage differential is boosted through a charge pump, and is regulated to a desired voltage (3 V) in order to use the hybrid harvester as a supply to common ICs.

![Figure 1. Hybrid energy harvester structure.](image)

2.1. RF and EM Rectifier Circuits

The signal from the RF harvester is rectified, and stepped up using a 7-stage threshold compensated rectifier to generate a positive DC voltage. Bias voltage required by the MOSFET at each rectification stage is supplied by the source terminal of the right adjacent transistor, as shown in Figure 2 [6]. The configuration compensates for the voltage drop at each stage to enhance step-up performance. A dummy MOSFET-capacitor pair (\(M_d\) and \(C_d\)) in the last stage minimizes voltage fluctuation with load.

The harvested voltage at the EM side is rectified to a negative potential with a self-powered AC/DC doubler circuit depicted in Figure 3, which utilizes active diodes to increase current capacity, and to minimize the forward bias voltage drop. However, active diodes require a power supply unlike passive counterparts. The comparators in the active diodes are powered internally by a passive AC/DC positive doubler, and a negative quadrupler constructed with diode-connected MOSFETs. The positive doubler with passive diodes generates the required gate to source voltage to improve the load current delivered by the active diode. Furthermore, the negative quadrupler with passive diodes generates a negative supply required to precisely turn off the active diodes, thus minimizing losses at the output.
Figure 2. 7-stage threshold compensated RF rectifier [6].

Operation principle of the circuit in Figure 3 is as follows: When the input voltage is positive and \( V_x \) potential is higher than GND, the comparator Comp1 turns the \( M_{N1} \) transistor ON. As a result of this, the storage capacitor \( C_1 \) between the input and \( V_x \) node is charged up to negative peak voltage of the input. When \( V_x \) falls below ground potential, the switch \( M_{N1} \) is turned OFF, and a negative charge is stored on the capacitor \( C_1 \). Similarly, when the input is negative and the \( V_x \) potential is below negative output voltage \( V_{out} \), switch \( M_{N2} \) is turned ON, and current flows from \( V_{out} \) to \( V_x \) since \( V_{out} \) has lower potential compared to \( V_x \). When \( V_{out} \) falls below \( V_x \), the switch is turned OFF and a doubled negative voltage is stored on the output storage capacitor \( C_{out} \).

2.2. DC/DC Converter and Voltage Regulator
In the next stage of the circuit, the rectified dual rail output from EM and RF harvesters is fed to a DC/DC boost converter that utilizes a 4-stage cross-connected charge pump [7]. The charge pump is suitable for low voltage applications, and in contrast to the inductor based DC/DC converters, it is suitable for on-chip CMOS integration. The non-overlapping clocks required by the charge pump are generated by a low power current-starved ring oscillator in Figure 4. The frequency of the oscillator is controlled through the biasing of the current starving transistors. The bias generator circuit includes a PMOS transistor operating in triode region (\( M_1 \)), and helps to determine the bias current of the oscillator. The voltage regulator, shown in Figure 5, provides bias feedback based on the output voltage to modulate oscillator frequency through current starving MOSFETs, and hence adjusts the pumped current. The regulator consists of a voltage divider, a reference (\( V_{REF} \)) generator [8], and a comparator to detect the error between the divided output voltage and the reference.

The operation of the voltage regulator circuit is as follows: The oscillator is pushed to maximum frequency until the output voltage (\( V_{OUT}-V_{SS} \)) reaches the desired value (3 V), at which point the divider output reaches \( V_{REF} \), and the comparator readjusts the frequency of the oscillator.
In the comparator circuit, NMOS input transistors are utilized to make the input common mode close to low voltages since the circuit compares the voltage reference and divider which are both at low levels. The circuit is composed of three stages, which enhances the precision and reduces the ripple at the output. The bias of the subthreshold comparator \(V_{\text{BN}}\) is also generated from the same reference circuit, which reduces power dissipation and sensitivity to supply voltage.

3. Test Results and Discussion

The hybrid interface circuit is designed and implemented in UMC 180 nm CMOS technology. Figure 6 shows the die micrograph of the implemented CMOS harvester chips. RF circuit is isolated from the remaining components on a different die in order to separate its substrate and minimize the body effect on the MOSFETs. The only off-chip components of the system are storage capacitors of the EM rectifier and resistors at the voltage divider, which can be integrated on the CMOS chip in a future stepping for cost reduction.

Figure 6. Micrograph of the RF and EM harvester chips.

Figure 7. Variation of the output voltage with respect to the RF input power and EM harvester vibration frequency.

The hybrid system has been tested at different vibration frequencies and RF input power levels. EM harvester has been stimulated with 1g peak-to-peak acceleration at 8.5-11.5 Hz input frequency range. -20 dBm to -5 dBm input power has been applied to the RF harvester. Figure 7 presents variation of the output voltage with various input conditions at 1 M\(\Omega\) load. As the RF input power increases, the output voltage ramps up, and attains the desired voltage (3V). It is observed that the required RF power for obtaining 3 V output varies with vibration frequency, and both harvester sources contribute to the generated power and voltage. Figure 8 shows the input and output voltage waveforms when the EM harvester is stimulated with 1g vibration at 10 Hz, and RF harvester input is
-5 dBm at 900 MHz. The hybrid system successfully delivers a stable 3 V source with a ripple voltage less than 30 mV to 1 MΩ load. The low level ripple at the output shows the accuracy and sensitivity of the voltage regulator. The voltage regulator rapidly responds to the output voltage variation and tunes the boosting ratio of the charge pump. Figure 9 presents the current driving capability of the hybrid system when the EM harvester is stimulated with 1g vibration at 10 Hz, and RF harvester input is -5 dBm at 900 MHz. As depicted in the figure, the battery-like operation is verified at 3 V for a wide range of loads up to 18 µW of output power.

**Figure 8.** Waveforms of the EM harvester voltage and the generated 3 V hybrid system output voltage at 10 Hz and 1g vibration (RF input power: -5 dBm).

**Figure 9.** Variation of the output voltage with respect to the load resistance at 10 Hz and 1g vibration (RF input power: -5 dBm).

### 4. Conclusion

A self-powered and autonomous hybrid energy harvesting structure which utilizes the low frequency ambient vibrations and UHF RF signals is presented in this paper. The low frequency ambient vibrations are harvested by a small sized in-house EM harvester, and are rectified negatively by a self-powered autonomous rectifier. In contrast, the harvested RF signals are rectified by a 7-stage threshold compensated rectifier to a positive DC voltage. The rectified positive and negative voltages are then added serially by using the ground node as a reference. At the next stage, an on-chip DC/DC converter and a voltage regulator respectively boosts and stabilizes the rectified dual rail voltage to the desired 3 V output. The test results showed that the hybrid system provides 3 V stable output with 18 µW of output power for a wide range of input conditions while both of the harvesting sources contribute to the output.

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