A simple passive 390 mV ac/dc rectifier for energy harvesting applications

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Abstract. This paper reports a simple, discrete, ac/dc rectifier architecture intended for magnetic energy harvesters that functions with ac input voltages as low as 390 mV_{pk}. The proposed four NMOS rectifier (4NR) employs cross-connected, saturated-load NMOS inverters. The circuit is completely passive, exhibits good low-voltage performance, consists of only four components for small footprint, and requires no additional blocking diode to prevent power flow from the load. At 2 V_{pk} input, the 4NR exhibits a power efficiency of 93 % and 400 μW of output power. The 4NR is also successfully connected to an off-the-shelf TI BQ25504 dc/dc converter + battery management chip and shown to charge both capacitor and lithium-ion battery energy storage reservoirs.

1. Introduction

Miniature energy harvesters are a promising solution to extend system lifetime and to achieve autonomous operation of wireless devices and systems. Because most energy harvesters generate only μW to mW of power, they demand ultra-high-efficiency solutions for voltage regulation and power management of load-side energy storage elements (batteries/supercapacitors). Compared to thermoelectric or solar energy harvesters that generate dc outputs, vibrational energy harvesters typically generate low frequency (<1 kHz) sinusoidal output waveforms. Unfortunately, while there now exist many commercial energy harvesting power management chips that can accommodate dc voltage inputs (for thermoelectric or solar power sources), there are few (none?) that can accommodate low-amplitude (<1 V) ac inputs.

There are significant power electronic design challenges for harvesters that utilize magnetic (inductive/electrodynamic) transduction. Compared to piezoelectric or electrostatic vibrational harvesters, magnetic harvesters have much lower output impedances, meaning they generate lower voltages and higher currents. The harvester output voltage amplitudes are often below 1 V_{pk}, making traditional diode-bridge rectifiers an ineffective ac/dc solution. The reason is that a diode-based full-wave rectifier requires overcoming two forward-bias diode drops, which equates to ~1.4 V for pn diodes, or ~0.7 V for Schottky diodes. Fortunately there are other solutions. For energy harvesting applications, passive rectifiers are generally preferred over active rectifiers, since active rectifiers may draw too much power during standby mode. Of passive converters, cross-connected inverters and negative voltage converters are the most commonly used architectures. A negative voltage converter requires a second stage (either physical diode or active diode) to prevent backflow of current from the load to the source.
In this work, a four NMOS rectifier (4NR) architecture is proposed, which is similar to [1,2], but operates at much lower frequencies, and employs four discrete NMOS transistors, as opposed to complex floating-gate CMOS [1] or BiCMOS [2] integrated circuit technologies. Both simple ac/dc conversion and a fully functioning power management system are tested using an electrodynamic transducer [3] as the energy harvesting source. The measurements show that the 4NR achieves better low-voltage efficiency compared to other commonly used architectures.

2. Four NMOS Rectifier Circuit Design

The 4NR architecture is intended to balance important functional characteristics of an ideal ac/dc converter. First, for energy harvesting applications, the rectifier should have zero standby power consumption (fully passive) and should function (rectify) at the lowest possible input voltage amplitude. Second, the rectifier should have minimal ac/dc voltage drop (the voltage difference between the output dc waveform and the amplitude of the input ac waveform) and minimal dc voltage ripple. Third, in implementation, the ac/dc circuit should fit in a small footprint.

Figure 1: The proposed four NMOS rectifier (4NR) and two other comparison ac/dc rectifiers for benchmarking: Schottky diode bridge (SDB), and negative voltage converter (NVC+AD) with active diode.

Figure 1 shows the proposed 4NR circuit. It comprises two upper NMOS transistors connected in diode form and two lower NMOS transistors cross-connected to the input source. The circuit is essentially two saturated transistor load inverters that are cross-connected. Here, the upper “load” transistors are NMOS instead of PMOS as used in other CMOS inverter architectures [1,2,4,5]. In operation, only two transistors are working at any given time, one of the lower transistors (M1 or M2) acts as a switch which means it operates in the triode region, while one of the upper transistors (M3 or M4) is working in the saturation region given that is connected in diode form. For example, M1 will turn on to triode and M4 will turn on to saturation under the positive half-cycle of the sinusoidal waveform.

All selected NMOS are power FETs, which have low turn-on resistances, and therefore minimize conduction losses. Subsequently, the minimum operating voltage for this circuit is just the transistor threshold voltage (~390 mV in this case). Similarly, the voltage drop of the presented architecture is primarily due to the forward-bias voltage drop in the diode-connected transistor that is approximately equivalent to the threshold voltage. For this reason, the circuit is designed using NMOS instead of PMOS, because discrete NMOS transistors normally exhibit lower threshold voltages than PMOS.
3. Experimental Results

The 4NR is benchmarked against the two other common ac/dc architectures—a simple Schottky diode bridge (SDB) and a negative voltage converter with an active diode serving as a blocking diode (NVC+AD) [1,2] (Figure 1). The 4NR is then connected to a commercial dc/dc converter + battery management chip (TI BQ25504) to demonstrate successful charging of energy storage loads.

3.1. Experimental Methods

The rectifier circuits are simulated in SPICE, fabricated at the PCB level (Figure 2a), and then tested using an electrodynamic wireless power transmission (EWPT) receiver [3] as the ac input source. The EWPT receiver uses a magnetically excited resonating magnet to induce an ac voltage in the receiver winding (Figure 2b). The receiver operates at ~10 Hz and the receiver coil resistance is ~126 Ω. The amplitude of the receiver voltage can be increased (up to > 3V) or decreased (down to 0) based on the amplitude of the magnetic field supplied by the EWPT transmitter.

Figure 2: (a) Photographs of the electrodynamic wireless power transmission (EWPT) receiver, the three tested ac/dc architectures, and the TI BQ25504 dc/dc converter + power management chip (b) Block diagram of the EWPT system coupled with the power management electronics.

3.2. AC/DC Rectifier Measurements

First, each ac/dc rectifier is characterized by measuring the extracted power as a function of the load resistance for a constant excitation from the EWPT transmitter (constant magnetic field amplitude). Figure 3a shows the measured output power versus load resistance for a constant harvester excitation (in this case, an open-circuit voltage of 3.2 Vpk, which corresponds to ~2 Vpk for the optimal load resistance). The 4NR is shown to draw more power from the receiver than the other two architectures. Here a maximum of 400 μW is achieved for a load of 6 kΩ.

Next, the rectifier power efficiency is measured for different ac input voltages. Figure 3b shows the ac/dc rectifier efficiency (using matched load and a 47 μF smoothing capacitor) as a function of the operational ac input voltage (as measured with the matched load connected). At higher voltages, such as 2 Vpk input, the 4NR exhibits 93 % efficiency, which is better than the 91 % from the NVC and 76 % from the SDB. More importantly, at lower voltages, the 4NR is shown to function as low as 400 mVpk, whereas the other two rectifiers exhibit zero efficiency. In the case of the SDB, the circuit simply does not function. In the case of the NVC + AD, the circuit could successfully rectify 400 mVpk, but the power consumed by the active diode is larger than the power delivered to the load. Figure 3c shows the voltage drop for the different ac/dc converters under varying input voltages. Here, as expected, the 4NR shows larger voltage drop compared to the NVC+AD, but significantly lower than the SDB.
3.3. Full Power Management System

Because the rectified dc output of the passive rectifier is typically too low to directly charge a battery, an off-the-shelf TI BQ25504 dc/dc converter + battery management chip is added at the output of the 4NR (Figure 4). The BQ25504 steps up the rectified voltage, provides battery voltage protection, and intelligently manages the battery charging and load-side power management, which together maximize the power extracted from the energy harvester [6]. The system was designed for a 150 mAh Li-ion coin cell battery [7]. In operation, the harvester was shown to slowly charge the battery, evidenced by a few millivolt increase in the cell voltage over a period of a few minutes (due to the relatively low charging rate relative to the battery capacity). To better show charging capabilities, Figure 5 shows the system fully charging a 220 µF capacitor (instead of a battery) over a period of 70 s (1.76 mJ, corresponding to average load power delivery of 25 µW).

Figure 3: (a) Power versus load resistance for the tested ac/dc converters. (b) Power efficiency (output dc power / input ac power) versus ac input voltage for matched load cases. (c) Voltage drop (peak input ac voltage minus output dc voltage) versus ac input voltage for matched load cases.

Figure 4: Complete power management circuit for energy harvesters with ac output.
Figure 5: Waveforms (70 s duration) of ac input from harvester (yellow) and dc output to the load (blue) while charging a 220 μF capacitor via the 4NR and TI BQ25504 chip. The system automatically disconnects the energy harvester from the load when the capacitor is fully charged (at 4 V in this case).

Conclusion
In this paper, a four NMOS rectifier (4NR) ac/dc architecture is compared with two commonly used ac/dc rectifiers for energy harvesters. The proposed 4NR shows a higher extracted power and better performance at low voltages compared to two other traditional rectifier circuits. Specifically, under one test condition, the 4NR was able to extract a maximum of 400 μW, a 21% improvement compared to the other converters that were limited to 330 μW. Table 1 summarizes six additional design parameters comparing the different rectifier architectures. The 4NR is also able to rectify voltages down as low as 390 mV pk whereas the other converters did not function at such low input voltages. While the NVC+AD comes close with a minimum operating voltage of 410 mV, it has non-zero standby power, larger voltage ripple, and requires six components compared to four.

Table 1. Comparison between the three architectures.

|          | Standby Power Consumption | Power Efficiency | Minimum Operating Voltage | Voltage Drop (at 1 Vpk ac input) | Output Ripple Voltage | Number of Components |
|----------|---------------------------|------------------|--------------------------|----------------------------------|-----------------------|---------------------|
| 4NR      | 0                         | Excellent        | 390 mV                   | ~ 315 mV (Vt + Rdson)            | Small                 | 4                   |
| SDB      | 0                         | Poor             | >600 mV                  | ~ 540 mV (2Vfb)                  | Small                 | 4                   |
| NVC+AD   | 6 μW                      | Excellent        | 410 mV                   | ~ 170 mV (3Rdson)                | Large                 | 6                   |

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