A BRIDGE VOLTAGE DOUBLER AC/DC CONVERTER FOR LOW-VOLTAGE ENERGY HARVESTING APPLICATIONS

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Abstract: Efficient ac/dc rectification of low voltages is critical for the realization of fully-functional vibrational energy harvesting systems. This paper presents the design and experimental characterization of low-power ac/dc converter designed to operate with very low input voltage amplitudes (as low as 20 mV) for magnetic induction energy harvesters. The bridge voltage doubler provides a dc output voltage that is twice the ac input amplitude. A maximum efficiency of 92% was achieved for a 1 V input amplitude. Even with input amplitudes as low as 100 mV, efficiency could exceed 70%. The circuit also functioned properly when connected to a magnetic energy harvester device.

Keywords: ac/dc converter, rectifier, power electronics, active diode, voltage rectifier

INTRODUCTION

The growing emergence of microwatt to milliwatt motional/vibrational energy harvesting technology urges the development of low-power power management circuits. For vibrational energy harvesters, one specific need is ac/dc converter circuits that can operate at low input power and low voltage with acceptable efficiency (>80%). Most attention has been focused on circuits for piezoelectric harvesters [1-3], whose output voltage level is generally higher (typically >1 V) than similarly sized magnetic harvesters (typically <1 V). A lack of suitable low-voltage rectification solutions presents a substantial obstacle for the development of magnetically based vibrational energy harvesting systems [4].

Passive junction-based semiconductor diode bridges are generally not suitable for input voltage levels under 0.5 V due to the forward-bias voltage drop associated with the diodes. Alternatively, active MOS-based synchronized rectification are possible, where the rectification is implemented by controlling the conduction of MOSFET with a clock signal that is in phase with the input signal [5] This approach requires a drive voltage (control signal) that is higher than the threshold voltage of the MOSFET (typically ~0.4 V). This drive voltage may not be available without introducing complicated driving circuitry.

Alternatively, in an attempt to avoid the inherent forward-bias voltage drop of semiconductor diodes, active diodes have been used in wireless power transmission [6] and medical areas [7]. An active diode is a comparator-controlled switch that replaces junction-based diode. Recent works have explored combining a synchronized rectifier with an active diode for energy harvester application [8]. However, this approach suffers from the same voltage threshold limit of other self-driven synchronized rectifiers, and the minimum rectifiable input voltage was reported to be only 1.25 V [8].

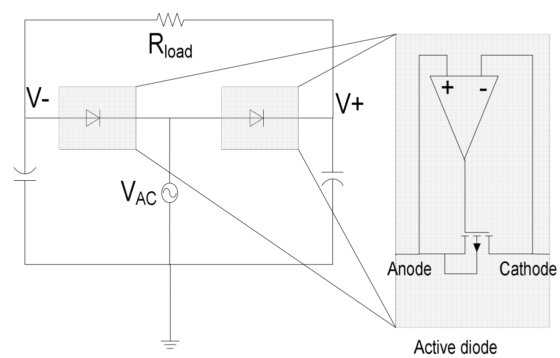

Fig. 1: A bridge voltage doubler with active diodes.

In this paper, a bridge voltage doubler circuit (Fig. 1) is demonstrated with active diodes, where the dc output voltage is twice the input ac amplitude. In such realization, input voltage amplitudes as low as 20 mV are successfully rectified. Since the rectified voltage is still quite small, an actual energy harvesting system may require additional voltage boost stages, for example, to charge a battery. While these circuits are not explored here, the voltage doubling effect of the bridge doubler can reduce the burden of subsequent voltage boost stages.

CIRCUIT DESIGN

The circuit design is described below. Using discrete components, the circuit was fabricated on a two-sided printed circuit board with a footprint of 1.54 cm^2 (Fig. 2).

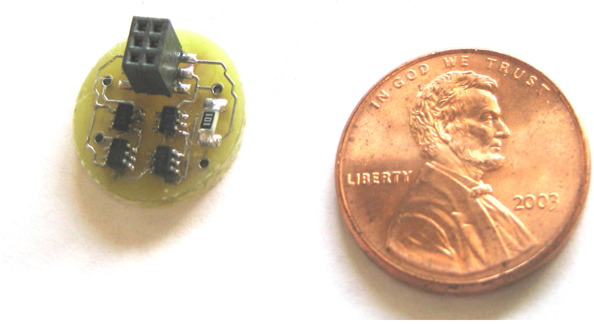

Fig. 2: A picture of the circuit board.

Table 1: Comparator output voltage requirements for different types of MOSFETs used in the positive and negative sides of the doubler.

		NMOS	PMOS
Positive Side		$V_{pos}^* > V_{max}^* + V_{th}^*$	$V_{pos} > V_{max} - \lvert V_{th} \rvert$
		$V_{neg}^* < V_{min}^* + V_{th}$	$V_{neg} < -\lvert V_{th} \rvert$
Negative Side		$V_{pos} > V_{th}$	$V_{pos} > V_{max} - \lvert V_{th} \rvert$
		$V_{neg} < V_{min} + V_{th}$	$V_{neg} < V_{min} - \lvert V_{th} \rvert$

* V_{pos}: positive output voltage of the comparator. V_{neg}: negative output voltage of the comparator. V_{max}: maximum input voltage. V_{min}: minimum input voltage. V_{th}: threshold voltage.

Active diode

The behavior of an ideal diode can be described as an intelligently controlled switch, whose on/off state is determined by comparing the voltage across the terminals. When the anode voltage is higher than cathode, the switch turns on; otherwise it turns off. An "active diode" is a circuit implementation of using active components to approximate this ideal behavior. Specifically, the switch is implemented by a MOSFET, whose source and drain terminals are connected to the input of a comparator. The output of the comparator is connected to the gate terminal of the MOSFET (Fig. 1).

The use of active components (i.e the comparator and MOSFET) introduces extra power consumption. However, with state-of-the-art low-power integrated circuits, this power consumption is typically much smaller than the power consumed in a junction-based diode. For example, the nanopower comparator MAX9119 by Maxim (used in the circuit here) has a minimum operation voltage of 1.6 V with supply current of 350 nA, yielding a quiescent power consumption of only 560 nW [9]. Comparing this to a typical Schottky diode with forward voltage of 0.3 V, the equivalent power is dissipated with a current flow of only 2 µA. Also, the forward-bias resistance of a Schottky diode is usually larger than the conducting resistance of a MOSFET.

Since the comparator requires a voltage supply, an external power supply was used in this paper. However, in practical implementation, this supply voltage could be sourced from a later stage in a more complete energy harvesting circuit. This external power input was taken into consideration for all efficiency calculations.

Bridge voltage doubler

The bridge voltage doubler is a conventional circuit topology that was commonly used in cathode ray tube televisions to generate high dc voltages. The circuit functions as two peak detectors, capturing the positive and negative peaks of the input voltage waveform. The load is connected across the positive and negative outputs of the peak detectors, where the load voltage is twice the input ac voltage. By replacing the junction-based diodes with active diodes, the circuit can operate at low input voltage.

MOSFET selection

The operating state of a MOSFET is controlled by the differential voltage between the gate and source terminals. Selection of MOSFET types and comparator output ranges becomes very important.

To avoid charge leakage through the body diode, the MOSFET must be connected in a way such that the body diode is oriented as shown in Fig. 1. Depending on whether NMOS or PMOS is used on each side of the doubler, the comparator output voltage must meet certain requirements in order to properly turn on or turn off the MOSFETs. These requirements are summarized in Table 1.

The comparator output voltage swing is determined in part by the supply voltages. For the MAX9119, the positive output is equal to the positive supply voltage minus 0.3 V, and the negative output voltage is the negative supply voltage plus 0.3 V [9]. From Table 1, it is concluded that the supply voltage requirement is lowest when PMOS is used for positive side and NMOS is used for negative side. In the actual circuit, Vishay SD1450DH (V_{th} = 0.3 V) and SD1499DH (V_{th} = -0.35 V) were used as NMOS and PMOS respectively. The comparators were supplied with +/-1 V.

Stabilization technique

The circuit shown in Fig. 1 cannot work properly when the load is too light (load impedance too high). The voltage across the MOSFET is too low to be sensed by the comparator when the current flow is small. One way to tackle this problem is to add a resistor in series with the MOSFET so that the input voltage "seen" by the comparator is amplified. However this will increase the conduction loss and reduce the efficiency.

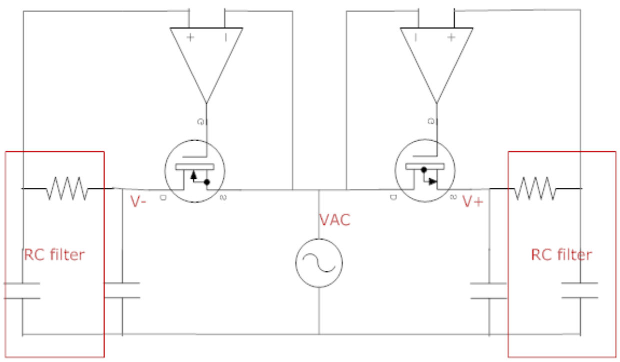

Fig. 3: Bridge voltage doubler with low pass filter.

Another method to overcome this problem is to add an RC filter, as shown in Fig. 3. The comparator input voltage is the voltage across the MOSFET plus the filter resistor. Therefore it is large enough to be detected. Since the RC filter is not part of the power flow path, no dc power is consumed on the filter resistor. However, because the feedback source is not the actual output, there is some ripple with the output voltage (Fig. 4). The ripple increases with increasing filter resistance.

EXPERIMENTAL

For characterization, a 20 Hz sine waveform was used as the input (0.02 – 1 V amplitude). The waveform was generated from an Agilent 33120A function generator, whose output impedance is 50 Ω. This mimics the output characteristics of a low-frequency magnetic induction energy harvester.

Low input voltage test

To demonstrate the low input voltage capability, the input voltage amplitude was gradually decreased, until the ripple exceeded 10%. To successfully rectify very low input voltages, the filter resistor has to be large in order to maintain a detectable voltage for the comparator input. This comes at the expense of increased ripple. For R = 100 Ω and C = 47 µF, an input voltage amplitude of only 20 mV was rectified, with a 10% ripple (Fig. 4). The same RC values were used throughout the test.

Efficiency and power measurement

In order to measure the power efficiency of the circuit, different load resistances were connected to the output. At different input voltage amplitudes, input and output power were measured. The average input power is given by,

$$P_{in} = \frac{1}{T}\int_0^T [v_{in}(t) i_{in}(t) + v_{supply}(t) i_{supply}(t)]dt \qquad (1)$$

where v_{in} and i_{in} are instantaneous input voltage and

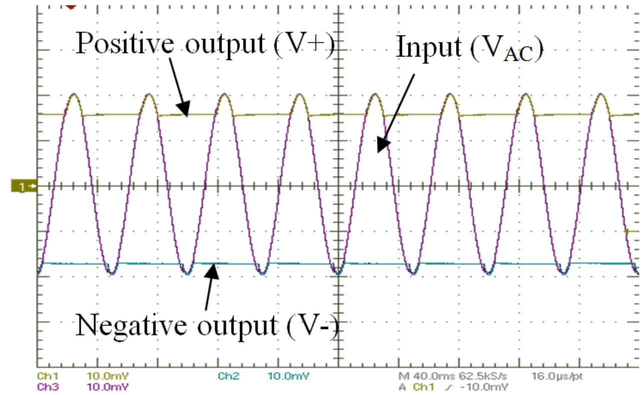

Fig. 4: Open-circuit waveforms with input amplitude of 20 mV.

current, v_{supply} and i_{supply} are the instantaneous supply voltage and current to the comparators, and T is the duration of measurement, which is greater than 10 cycles.

The comparator supply voltages and currents are mostly dc. Therefore the power contribution of the power supply is approximately $V_{supply}*I_{supply}$. These were measured and supplied using two Keithley 2400 Sourcemeters. The input voltage is directly measured by an oscilloscope (Tektronix TDS5104B), whereas a 0.1 Ω current-sensing resistor was connected in series at the input in order to measure the input current. The voltage across the current-sensing resistor was amplified by a low noise amplifier (SRS SR560).

A plot of efficiency vs. load resistance at different input voltage amplitude is shown in Fig. 5. A maximum efficiency of 92% was achieved with 1 V input voltage amplitude. A maximum efficiency of 74% was obtained at 0.1 V.

While efficiency is important, the total output power may be more relevant for energy harvesting system. Fig. 6 shows the output power increases with increasing input voltage as expected. The maximum output power was always achieved around 200 Ω regardless of input voltage amplitude. The equivalent output impedance of the rectifier is related to the load condition and the shape of the waveform. Based on the maximum power point, the circuit output impedance is believed to be around 200 Ω.

Functionality test with harvester input

A real-world test was performed by connecting the circuit to a magnetic energy harvester [10]. The harvester was shaken by hand, generating a randomized voltage waveform with amplitude <0.3V. It can be seen from the no-load output voltage waveforms shown in Fig. 7 that the maximum and minimum points of the waveform were precisely tracked. The charge is held in the capacitors when the

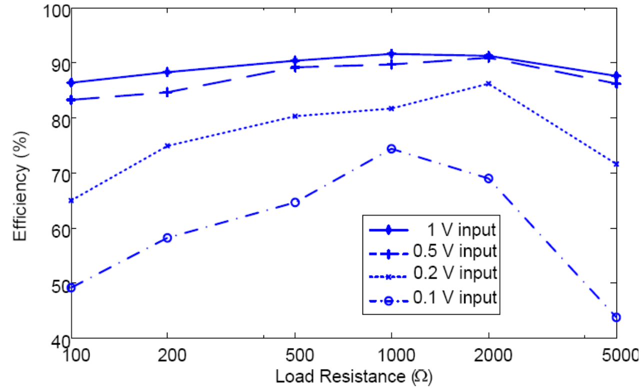

Fig. 5: Efficiency vs. load resistance for different input voltage amplitudes.

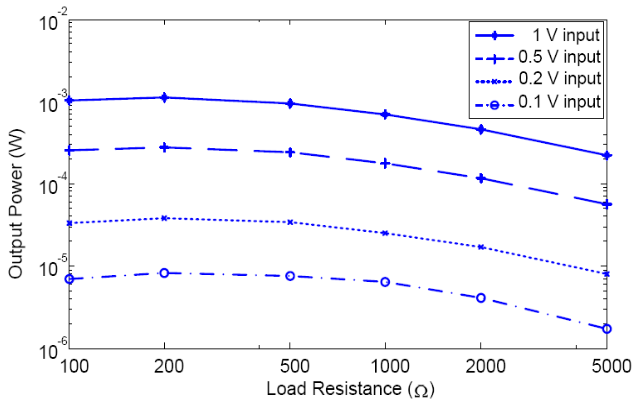

Fig. 6: Output power vs. load resistance for different input voltage amplitudes.

output voltage is lower than the capacitor voltage. A slight decay is observed in the dc voltages, because of the finite input impedance of the oscilloscope, i.e. some charge is leaking off into the scope.

CONCLUSION

A bridge voltage doubler circuit using active diodes is introduced to rectify low-amplitude voltages from energy harvester with high efficiency. The circuit successfully rectified an input voltage as low as 20 mV. The power loss of the active components is minimized by proper selection of MOSFET types. An RC filter based stabilization technique is introduced to guarantee functionality at light load condition. The resistance value of the RC filter plays an important role in the circuit. Higher resistance leads to lower input voltage limit but lower efficiency. The circuit was also demonstrated to work when connected to a real magnetic energy harvester with peak output voltage lower than 0.3 V.

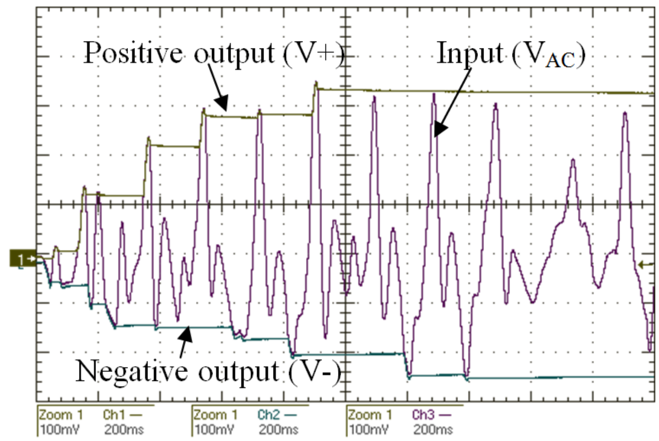

Fig. 7: Open-circuit waveforms with energy harvester input. Voltage scale = 100 mV/division.

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