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StudentZone—ADALM2000 Activity: Active Rectifiers

Doug Mercer, Consulting Fellow, and
Antoniu Miclaus, System Applications Engineer

Objective

The objective of this lab activity is to examine active rectifier circuits. Specifically, one that combines an op amp, a low threshold P-channel MOSFET, and feedback to synthesize a one-way current valve or rectifier with less forward drop than a conventional PN junction diode.

Background

Power supplies that use conventional diodes to rectify an AC voltage to obtain a DC voltage must rectify certain inherent inefficiencies. A standard diode or ultrafast diode can have a 1 V forward voltage or higher at its rated current. This forward drop of the diode is in series with the AC power source, which lowers the potential DC output voltage. In addition, this drop-in voltage multiplied by the current supplied through the diode can represent significant power dissipation and heat generation.

The lower forward voltage of Schottky diodes is an improvement over a standard diode. But Schottky diodes also have a built-in fixed forward voltage. Higher efficiencies can be achieved by actively switching MOSFET devices synchronously with the input AC waveform to emulate diodes, taking advantage of the FET's lower conduction losses. Active rectification, often referred to as synchronous rectification, means switching the FET device on and off at an appropriate point in the AC waveform according to the polarity, so it acts as a rectifier conducting current only in the desired direction.

Unlike the situation with the junction diode, conduction losses depend upon ON resistance ($R_{DS(ON)}$) and current. Choosing a large enough FET with a low $R_{DS(ON)}$ reduces the forward voltage drop to a fraction of what any diode can achieve. Hence, the synchronous rectifier will have a much lower loss than a diode, helping improve the overall efficiency.

Having to synchronize the gate signal used to turn on and off the FET complicates the circuit design over diode-based rectifiers. This complexity is often a better alternative to the added complexity caused by having to remove the heat generated by the diodes. With ever increasing efficiency requirements, there is often no better alternative than to use synchronous rectification.

Materials

- ADALM2000 Active Learning Module
- Solderless breadboard
- Jumper wires
- One AD8541 CMOS op amp with rail-to-rail input/output
- One ZVP2110A PMOS transistor (or equivalent)
- One 4.7 µF capacitor
- One 220 µF capacitor
- One 10 Ω resistor
- One 2.2 kΩ resistor
- One 47 kΩ resistor
- One 1 MΩ resistor

Directions

Build the simple half wave rectifier circuit shown in Figure 1 on your solderless breadboard. An active gate drive circuit uses an op amp (AD8541) to sense when the AC input waveform, from the output of the AWG, is more positive than the output voltage, V_{OUT}, and to turn on the PMOS transistor, M1. The circuit provides active rectification for AC voltages as low as the minimum power supply voltage for the op amp (2.7 V for the AD8541) or the gate threshold voltage of the PMOS device (typically 1.5 V for the ZVP2110A). At lower input voltages, the MOSFET's back-gate to drain diode takes over as an ordinary diode rectifier.

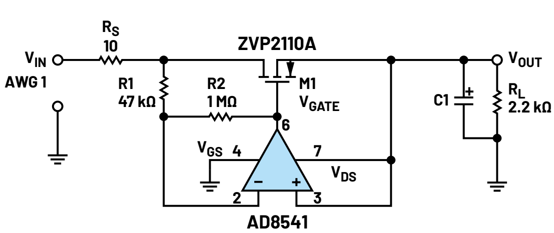


Figure 1. Active half wave rectifier with self-powered op amp.

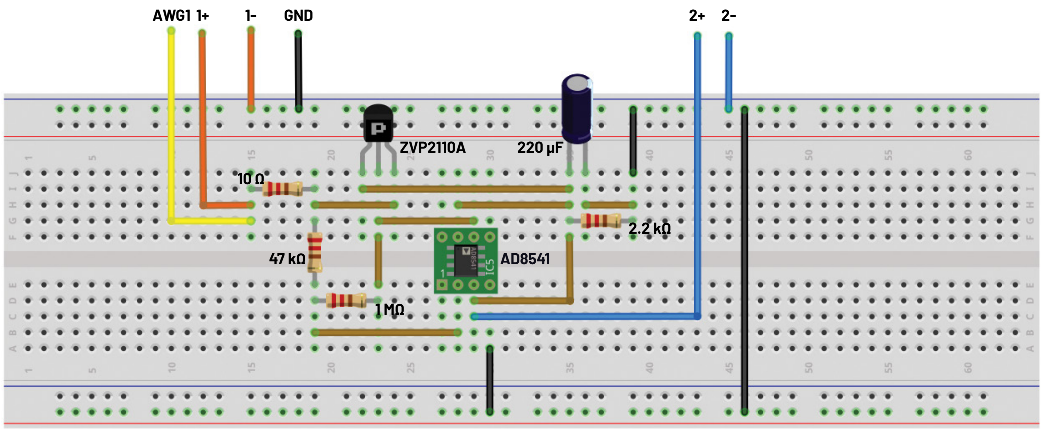


Figure 2. Active half wave rectifier with a self-powered op amp breadboard circuit.

The op amp will turn on the PMOS transistor when V_{IN} is larger than V_{OUT} according to the following equation:

$$V_{GATE} = V_{OUT} - \left(\frac{R2}{R1}\right)(V_{IN} - V_{OUT}) \qquad (1)$$

Where (voltages with respect to ground):

V_{GATE} is the voltage at the gate of M1

V_{IN} is the AC input voltage

V_{OUT} is the output voltage at C1 and R_L

You can relate the input and the output voltages to the PMOS's drain-to-source, V_{DS}, and gate-to-source voltage, V_{GS}, according to the following equation:

$$V_{DS} = V_{IN} - V_{OUT}$$

$$V_{GS} = V_{GATE} - V_{OUT}$$

We can combine these equations to relate the MOSFET's gate drive to a function of the drain-to-source voltage:

$$V_{GS} = -\left(\frac{R2}{R1}\right)V_{DS} \qquad (2)$$

If the value of R2 is 21 times larger in value than R1 (1 MΩ/47 kΩ), a 75 mV drop across the M1's drain-to-source voltage, V_{DS}, is sufficient to turn on the PMOS transistor with a threshold voltage of –1.5 V. Larger ratios of R2 to R1 could be used to either lower the input to output voltage drop or to accommodate transistors with higher threshold voltages.

The op amp is powered from the output smoothing capacitor C1 so no additional power supply is necessary. There are certain requirements for the op amp chosen for this circuit. The amplifier must have rail-to-rail inputs and outputs and demonstrate no phase inversion of the gain when operated near the power supply rails. The op amp's bandwidth limits the frequency response of the circuit. Low supply current op amps are often chosen for this application for efficiency which generally results in low bandwidths and slew rates. At higher AC input frequencies, perhaps higher than 500 Hz, the amplifier's gain will begin to decline. The AD8541 single-supply CMOS op amp has all of these requirements and a small supply current of only 45 µA.

Hardware Setup

Breadboard connections of the active half wave rectifier with self-powered op amp are presented in Figure 2.

Procedure

AWG1 is connected as V_{IN} and should be configured as a sine wave with an amplitude greater than 6 V peak-to-peak, zero offset, and a frequency of 100 Hz. The scope inputs are used to monitor various points around the circuit such as V_{IN}, V_{OUT}, the voltage across R_S and thus the current through R_S, and the gate of M1.

Start by using the large value 220 µF capacitor for C1. The 220 µF and 4.7 µF capacitors are polarized, so be sure to connect the positive and negative terminals to your circuit correctly.

Use the two scope inputs to monitor the input AC waveform at V_{IN} and the DC output wave form at V_{OUT}. V_{OUT} should be very close to the peak value of V_{IN}. Now replace the large 220 µF capacitor with the much smaller 4.7 µF capacitor. Observe the change in the waveform seen at V_{OUT}. When V_{OUT} is closest in value to V_{IN}, compare that interval of the AC input cycle with the voltage at the gate of transistor M1.

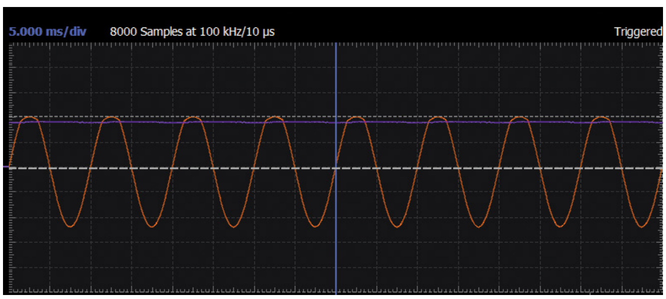


Figure 3. V_{OUT} and V_{IN} at 220 µF capacitor in a Scopy plot.

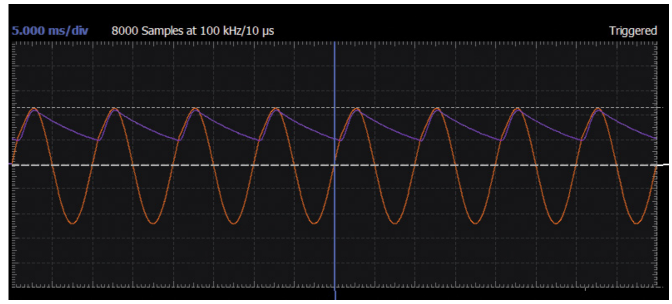


Figure 4. V_{OUT} and V_{IN} at 4.7 µF capacitor in a Scopy plot.

With Scope Channel 2 connected across shunt, the 10 Ω resistor R_S, use the measure feature to obtain the peak and average value of the current. Compare the average value with the DC in the 2.2 kΩ load resistor R_L you calculate based on the voltage you measure at V_{OUT}. Repeat this measurement for both the 220 µF and 4.7 µF capacitor values.

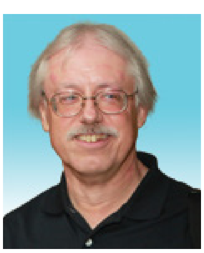
Other Uses for This Circuit

There are other potential uses for a circuit that essentially allows current flow in only one direction with very low voltage drop across the switch. In battery chargers, where the input power source might be intermittent such as a solar panel or wind turbine generator, it is necessary to prevent the battery from discharging when the input power source is not generating a high enough voltage to charge the battery. Generally, a simple Schottky diode is used for this purpose but as was pointed out in the background section this can lead to losses in efficiency. If an op amp with sufficiently low operating supply current is employed, this can often be lower than the reverse leakage current in a large Schottky diode.

Question:

1. Can you name several real-life applications for active rectifiers?

You can find the answer at the StudentZone blog.



About the Author

Doug Mercer received his B.S.E.E. degree from Rensselaer Polytechnic Institute (RPI) in 1977. Since joining Analog Devices in 1977, he has contributed directly or indirectly to more than 30 data converter products and holds 13 patents. He was appointed to the position of ADI Fellow in 1995. In 2009, he transitioned from full-time work and has continued consulting at ADI as a fellow emeritus contributing to the Active Learning Program. In 2016, he was named engineer in residence within the ECSE department at RPI. He can be reached at doug.mercer@analog.com.

About the Author

Antoniu Miclaus is a system applications engineer at Analog Devices, where he works on ADI academic programs, as well as embedded software for Circuits from the Lab®, QA automation, and process management. He started working at Analog Devices in February 2017 in Cluj-Napoca, Romania. He is currently an M.Sc. student in the software engineering master's program at Babes-Bolyai University and he has a B.Eng. in electronics and telecommunications from Technical University of Cluj-Napoca. He can be reached at antoniu.miclaus@analog.com.