	Diode 04 - Rectifiers

This project deals with one of the most important uses of the diodes, rectifying a signal.

BOM	Diodes: 4x 1N4148 Capacitor: 10µF Resistors: 2x 1k Ω, 2x 10k Ω, 100k Ω Two additional resistors to be calculated

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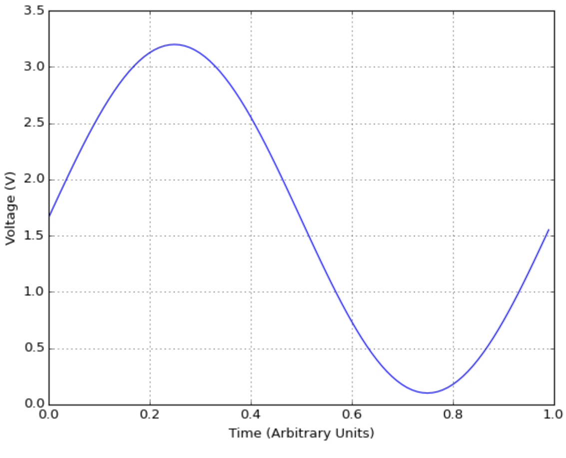
Introduction

One of the main uses of the diodes is signal rectification. This very useful in two important electronic domains: power supplies and signal demodulation. In the case of power supplies, most electronic devices power on DC voltages, but we get on the wall socket an AC voltage. So, most electronic devices that are connected to mains need to rectify and filter the AC voltage to obtain a DC voltage to power its electronics.
In the case of over the air signal transmission, like AM broadcasts, the audio signal is transmitted by modulating an AM radio frequency carrier. There are other systems that use amplitude modulation like FSK data transmissions and most Infrared remote control units.
In order to remove the carrier from the amplitude modulated signal, rectification can also be used.
In this document we will analyze the basic rectifier and we will use it do rectify and filter a sine wave. We will also use it to demodulate and amplitude modulated signal.
But, before we start working with the rectifier, we will need to deal to a voltage range problem associated to the SLab system. This will also serve us to introduce the bridge excitation of circuits.

Using bridges for more voltage range

The SLab system uses a microcontroller (MCU) development board to generate and measure the circuit under test (CUT) signals. Most modern MCUs operate at low voltages. In the case of the F303RE official SLab hardware board solution we use a 3.3V voltage supply. That means that both the signals we generate and we measure need to be inside the range from GND to Vdd.
If we want to generate a sine wave inside this voltage range we are limited to a signal like the one on the figure:

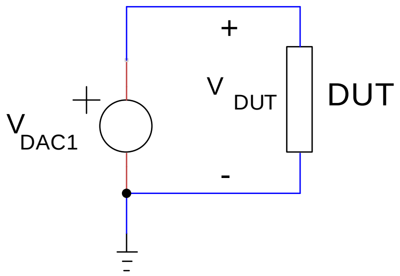


Observe that the signal don't go from 0 V to 3.3 V but from 0.1 V to 3.2 V. We are further limited by the fact that the buffers we use, although being full rail, need some voltage margin (several mV) from the supplies to operate, so we leave a 100 mV margin to the supplies.

All in all, our maximum peak to peak amplitude is 3.1 V and our amplitude is 1.55 V. Taking into account that a basic rectifier has a 0.7 V drop, that gives a quite low output voltage. The problem is worse if we use a more advanced bridge rectifier that has, as we will see later, a two diode 1.4 V drop. In that case we obtain practically no signal at the rectifier output.

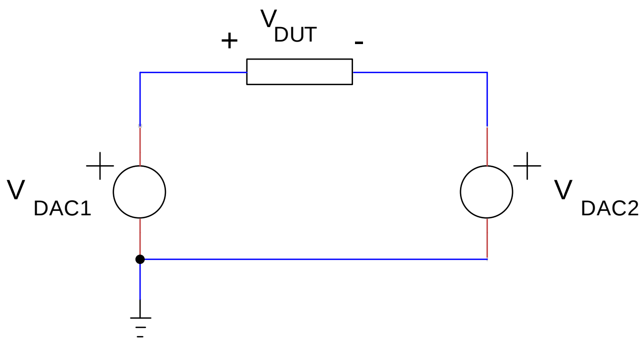
In order to cope with this problem we need to increase the voltage range we provide to our circuits. A doubled range of 6.2 V instead of 3.1 V would be enough. One way to obtain that would be to use an external supply and a specific new driver circuit to interface with the hardware board, but that will complicate too much the measurement setup. A second way is the use of **bridge configurations**.

Normal grounded configurations define all supplies respect to a common ground node. So, a two terminal device under test (DUT) will have one grounded terminal and the other terminal connected to a voltage supply.



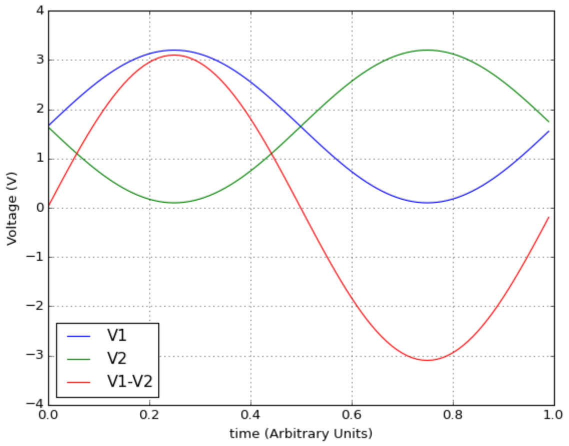
If the DAC 1 voltage is generated by a system powered between 0 V and 3.3V, the maximum voltage at the DUT will be 3.3 V.

A bridged configuration, instead of grounding one terminal of the DUT, connects both terminals to two different supplies:

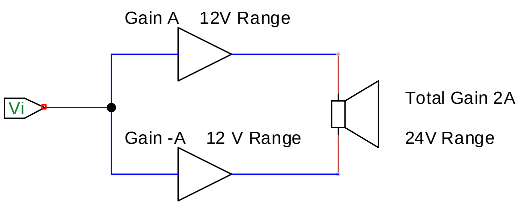


If both DACs can generate voltages between 0 V and 3.3 V, the maximum voltage on the DUT V_{DUT} will be 3.3 V (with DAC 1 at 3.3 V and DAC 2 at 0 V) and the minimum voltage on the DUT will be -3.3 V (with DAC 1 at 0 V and DAC 2 at 3.3 V) giving a total voltage range of 6.6 V.

In our case we will restrict ourselves to a range in the DACs between 0.1 V and 3.2 V. In the following figure we show a V1 sine wave between 0.1 V and 3.2 V and a V2 sine wave with the same range but opposite phase. The voltage difference between both signals will have a range between +3.1 V and -3.1 V.



This neat trick is typically used on audio amplifiers to double the voltage range on the output speakers. In the case of car audio we can get a +12 V to -12 V range (24 V total range) out of the 12 V car battery.

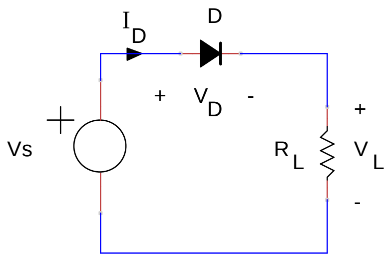


In the circuits described in this document we will use the bridge configuration to obtain the response of several rectifier circuits against inputs that can have a range of up to +3.1 V to -3.1 V. To round the numbers we will start using a +3 V to -3 V range.

During the measurements, using the bridge configuration, we must guarantee that the voltages read on the ADCs are always inside the supply range of the hardware board. This requirement is easy in resistive circuits, but in reactive circuits, like when using inductors or capacitors, it could be tricky.

The basic rectifier

The following circuit shows the basic rectifier circuit. This circuit takes an input voltage generated from a V_S voltage source. Rectifies it using a D diode and provides the rectified voltage to a R_L load.



In order to analyze the circuit we will use the large signal constant voltage diode model that assumes that the diode voltage is Vγ when conducts.

$$\begin{cases} V_d = V_\gamma & I_d \geq 0 & ON\ \ State \\ I_d = 0 & V_d \leq V_\gamma & OFF\ State \end{cases}$$

The diode can only be in two states: ON or OFF. In ON state Vd = Vγ. We can obtain V_L as function of V_S and Vγ in this case. As, the circuit in ON state is linear, $V_L(V_S)$ will be linear response.

The model requires that Id ≥ 0, so we can also calculate Id and check the range of input voltages that make true the inequation.
If you perform the analysis you should get:

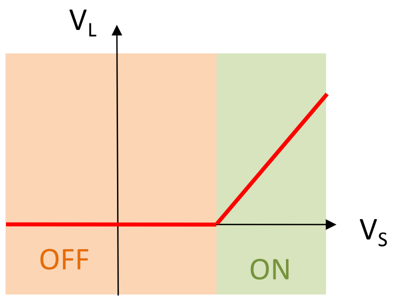
$$V_L = V_S - V_\gamma \qquad V_S \geq V_\gamma$$

1	Solve the circuit for the ON state and check that the solution and the conditions you get are the above ones.

In OFF state, current in the diode is zero and we require that Vd ≤ Vγ. If you solve the circuit for this case you should get the following solution and condition for V_L.

$$V_L = 0 \qquad V_S \leq V_\gamma$$

As the diode can only be in two states, the condition for V_S in OFF state need to be complementary to the one for the ON state. This is not mathematically exact as $V_S = V\gamma$ is compatible and give the same solution to both states.



The solution for the OFF state for every V_S value below $V\gamma$ whereas the solution for the ON state is valid for every value of V_S over $V\gamma$. The solution $V_L(V_S)$ for each state is a straight line and, as both state solutions are true for $V_S = V\gamma$ the two lines crosses just at this point.

2

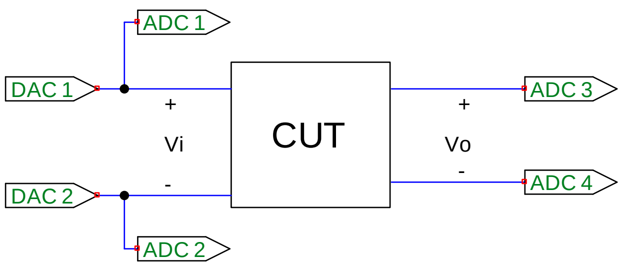
Solve the circuit for the OFF state and check that the solution and the conditions you get are the expected ones.

Draw in a graph $V_L(V_S)$ assuming $V\gamma$=0.7 V for V_S voltages between -3 V and +3 V. It should be similar to the above figure.

The curve you have just drawn is the Input to Output DC response of the rectifier circuit. Now we will measure it to test if we get same values obtained in the previous calculations.

As we said before, we will use a bridge configuration to test the rectifier circuits. We could perform the measurements by combining two DC sweeps but we have a ***curveVVbridge*** command in the SLab DC module that eases the measurements.

The ***curveVVbridge*** draws the Input to Output DC curve of a circuit that has its input driven by DAC 1 and DAC 2 in bridge configuration. It uses ADCs 1 and 2 to measure the input voltage and ADCs 3 and 4 to measure the output voltage.

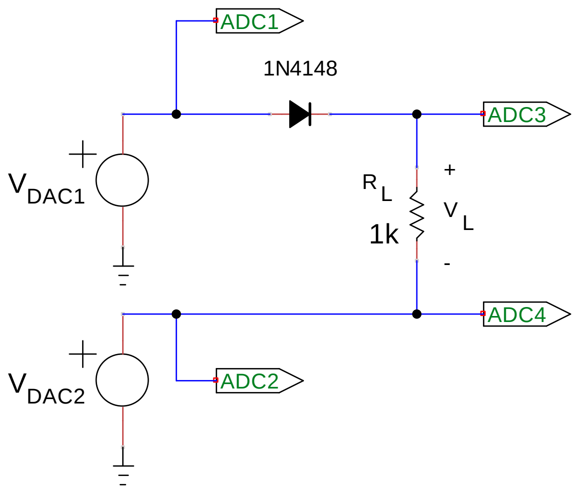


The command syntax of this command is:

curveVVbridge(vp, vn, vi, wt, returnData)

Where **vp** is the maximum voltage of DAC 1 and **vn** is the maximum voltage of DAC 2. The rest of parameters are optional and you can check the full description in the DC module reference document.

For the D diode we will use a 1N4148 device and we will use a 1 kΩ resistor for R_L. The following schematic shows all the connections on the test circuit. Observe that the ground terminal is not directly connected to any of the components you will mount on the breadboard.



After mounting the components we open a Python console, import the slab module and we connect to the board.

Then we can ask for the DC Input to Output response of the circuit after importing the SLab DC module:

```
>>> import slab_dc as dc
>>> dc.curveVVbridge(3,3)
```

🛠	**3**	Perform the proposed measurements. Compare obtained curve with the one you have drawn on 2.

The two curves should match quite well, perhaps the V_S value that defines the transition from the OFF to the ON state is not exactly the same but it should be near.

Now that we have obtained the DC curve, we can test the circuit against a sine wave. In order to generate a sine wave we will provide on DAC 1 and DAC 2 two sine waves with minimum at 0.1 V and maximum at 3.1 V, with opposite phases, so their functions will be:

$$V_{DAC\ 1} = 1.6V + 1.5V \cdot sin(\omega t)$$

$$V_{DAC\ 2} = 1.6V - 1.5V \cdot sin(\omega t)$$

So the voltage at the input of the circuit will be:

$$V_i = V_{DAC\ 1} - V_{DAC\ 2} = 3V \cdot sin(\omega t)$$

The following code configures those sine waves with 100 data points and 50 Hz frequency:

```
>>> slab.waveSine(0.1,3.1,100)
>>> slab.setWaveFrequency(50)
>>> slab.waveSine(3.1,0.1,100,second=True)
```

Now we configure the transient capture to record five full waves and we perform a measurement, with both DACs, storing all the four ADC channels.

```
>>> slab.tranStore(500,4)
>>> t,a1,a2,a3,a4 = slab.wavePlot(dual=True, returnData=True)
```

It is not easy to see how the circuit operates from the curves drawn in the last plot, but this plot is important to check that none of the ADC readings saturate at 0V or 3.3V.
In order to obtain the input and output voltage we will calculate them from the ADC readings and plot them afterwards:

```
>>> vi = a1 - a2
>>> vo = a3 - a4
>>> slab.plot1n(t,[vi,vo],"","time (s)","Vi,Vo (V)")
```

You should see that only the positive part of the input signal passes the diode and reaches the load, for the negative part of the input signal, the load voltage is zero.

You can also see the voltage on the diode:

```
>>> vd=vi-vo
>>> slab.plot11(t,vd,"","time (s)","Vd (V)")
```

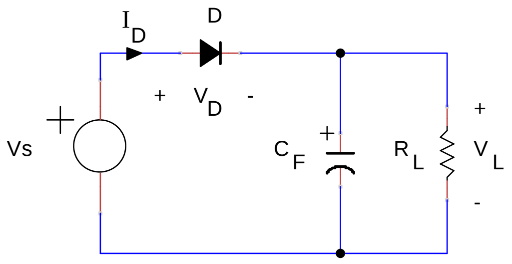
Zoom in the positive region. You should get a voltage drop between 0.6 V and 0.7 V when the diode conducts in the ON state, and the input voltage when it blocks in the OFF state.

🛠	**4**	Measure, as requested the response against a sine wave. Check both the voltage on the load and on the diode.

Filtering the output

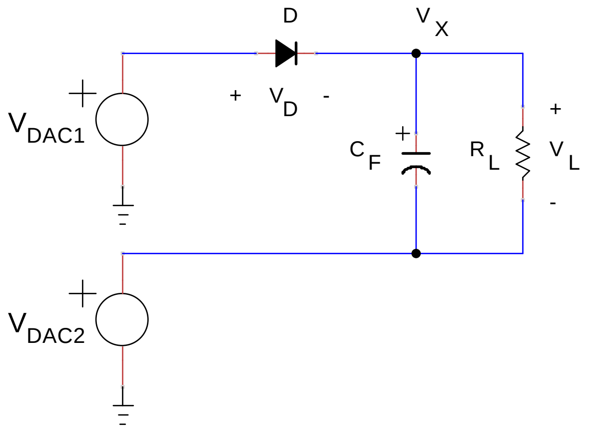
The previous circuit rectifies the input signal as it only lets pass the positive part of it, but the output voltage is not DC as it changes with time. If we want to use the rectifier to generate a DC voltage we must filter the output signal.

The easiest way to filter the signal is to add a capacitor in parallel with the load.



The capacitor, as it blocks the DC current does not change the DC curve of the circuit, but it has a great impact on its transient behavior. We could try to analyze this circuit before measuring it, but, this time, having the response at hand makes it easier to explain its behavior.

So, we will use the following circuit in bridge configuration. Note that V_L is the voltage between the two load terminals and V_X is the voltage between the load positive terminal and ground.



This circuit is tricky to be measured due to the fact that the positive load terminal can go outside of the supply range of the hardware board. In fact, using a time varying signal, diodes and capacitors are the basics of several voltage multiplying topologies.

The following lines explain the problem and propose a solution. If you don't understand the problem or don't want to deal with this kind of issues, you can skip the orange shaded section that follows.

Bridge hazards considerations

Capacitors tend to conserve its voltage. If $V_{DAC\ 1}$ is 3.1 V and $V_{DAC\ 2}$ is 0.1 V you will charge the capacitor to about 2.3V (taking into account the drop on the diode). If you now increase $V_{DAC\ 2}$ to 3 V and reduce $V_{DAC\ 1}$ to 0.1 V you will put the diode on OFF state and, as the capacitor conserves its voltage when current is zero, you could put the positive terminal V_X of the load at a voltage of:

$$V_{X\ max} = V_{DAC\ 2} + V_C = 3.1V + 2.3V = 5.4V$$

This voltage is over the supply voltage of the hardware board and two hazards could take place: First, the ADCs cannot measure over 3.3V, so the reading will saturate at 3.3V. Second, you will trip the ADC buffer opamp protection circuits and, eventually, damage them.

In order to prevent any hazard, we need to guarantee that we do not try to measure any voltage outside of the supply range of the hardware board. In order to do that, we will restrict the DAC voltages to a minimum of 0.1 V and maximum of 2.1 V. That way, C_F would have a maximum value of 1.3 V (considering a 0.7 V diode drop). In the worst case, if the diode drop was 0 V, we will get a maximum 2 V voltage. That way, the maximum voltage at the positive terminal of the load will be:

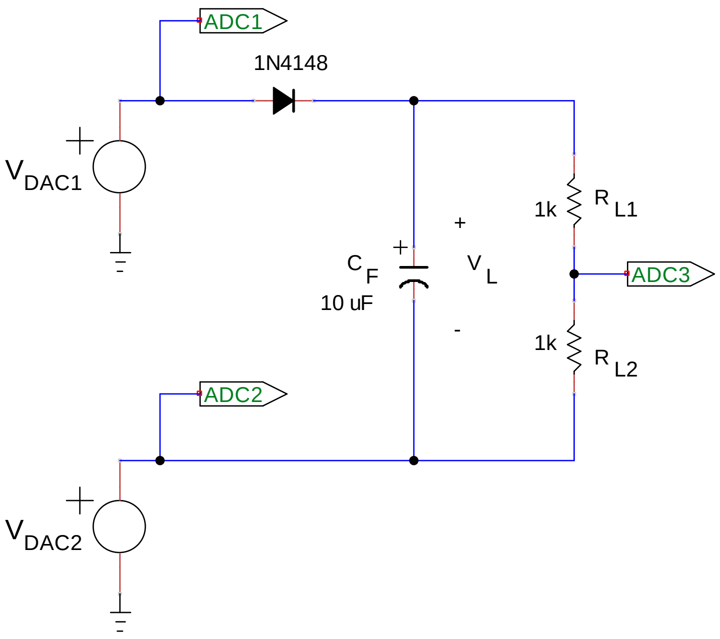
$$V_{X\ max} = V_{DAC\ 2} + V_C = 2.1V + 2.0V = 4.1V$$

That voltage is still outside of the measurable range of the ADCs so we will need to deal with that. The maximum voltage on DAC 2 is 2.1 V, and we want the maximum voltage on any ADC to be 3.2 V. That gives us a 1.1 V differece. As the load voltage can be up to 2 V we need to reduce it in half, so we will use two series resistors for R_L and measure the node that connects them.

So, in order to safely measure the circuit we will use the following schematic. It guarantees that, if the DAC voltages are between 0.1 V and 2.1 V, the voltage on the ADC 3 will be within its safe range. In order to calculate the load voltage we just need to calculate:

$$V_L = 2(V_{ADC\ 3} - V_{ADC\ 2})$$

Note that the load resistance is now 2 kΩ as both resistors are in series.



The generation code for the new waves will be:

```
>>> slab.waveSine(0.1,2.1,100)
>>> slab.setWaveFrequency(50)
>>> slab.waveSine(2.1,0.1,100,second=True)
```

In order to measure the circuit we will use the following code. This time is slightly different because we only use three ADCs.

```
>>> slab.tranStore(500,3)
>>> t,a1,a2,a3 = slab.wavePlot(dual=True, returnData=True)
```

As in the previous case it is difficult to understand the circuit operation from the curves, but we can use them to check that none of them are saturated at GND or Vdd voltages. After this check, dismiss the curves and calculate and draw the input and output voltages of the circuit:

```
>>> vi = a1 - a2
>>> vo = 2*(a3 - a2)
>>> slab.plot1n(t,[vi,vo],"","time (s)","Vi,Vo (V)")
```

🛠	**5**	Perform the requested measurements. Check that no ADC saturates and obtain Vi and Vo as function of time.

The input should be a sine wave between -2 V and 2 V and the output should be have a sawtooth shape.

The SLab system doesn't use continuous waves, waves are only generated during the measurements. That is good in this case because we can learn how the circuit operates from the beginning. The following lines describe how the circuit works:

- Before the measurement starts, the capacitor is discharged so its voltage is zero.

- The Vi input sine wave starts at zero and goes up.

- No change is seen on the output voltage Vo until the input voltage reaches the threshold Vγ voltage of the diode. Diode is in OFF state until this time. If you zoom in the image you will see that output voltage starts to rise when Vi reaches about 0.7 V.

- From this point, until Vi reaches its maximum, diode is in ON state and Vo a diode drop Vγ below Vi.

- After Vi reaches the maximum, it starts to drop. The capacitor conserves its voltage so the voltage on the diode lowers and it goes to the OFF state.

- Voltage on the capacitor is not constant, however, because it is discharged through the resistor in a typical exponential fashion.

- Diode is kept in the OFF state until, on the next cycle, the Vi to Vo difference reaches Vγ and the diode returns to the ON state.

- From this point onwards, the response of the circuit repeats so it is periodic.

We can see that the ouput voltage is not a DC constant but has a ripple sawtooth signal. We can roughly calculate the ripple of the voltage from the exponential decay of the capacitor voltage.

When the diode is off, the capacitor and the load resistors are isolated from the rest of the circuit, so they will feature an exponential discharge:

$$V_L(t) = V_{L0} \cdot e^{-t/\tau} \qquad \tau = (R_{L1} + R_{L2})C_F$$

The maximum voltage on the capacitor is reached when the input sine wave is at its maximum, so:

$$V_{L0} = V_{L\,max} = V_{i\,max} - V_\gamma$$

The capacitor does not discharge during all the input signal period, as during part of the period the diode is ON. We can, however, obtain a maximum bound of the ripple considering a worse case where the discharge time is all the input signal period. The maximum ripple can be calculated then:

$$V_{L\,max} = V_{L0} \qquad\qquad V_{L\,min} = V_{L0} \cdot e^{-T/\tau}$$

$$\Delta V_{L\,max} = V_{L\,max} - V_{L\,min} = V_{L0} \cdot \left(1 - e^{-T/\tau}\right)$$

6 Obtain $V_{L\,max}$, $V_{L\,min}$ and ΔV_L for our case considering the signals applied to the circuit and the values of the components.

7 Compare the measurements in 5 with the calculation in 6.

It is normal that the measure ripple is lower than the calculated one, as the calculation is an upper bound for the ripple.

The ripple is too high in this circuit for the output to be considered DC. In order to reduce it we need to increase the time constant τ. In a power supply circuit, the load resistance in the worst case is calculated from the maximum output voltage and the maximum current the circuit shall provide. Then, the C_F capacitor is calculated from a ripple specification.

In our case, as we are only learning about the circuit, we will just increase R_{L1} and R_{L2} from 1 kΩ to 10 kΩ to increase 10 times the τ value.

8 Change R_{L1} and R_{L2} to 10 kΩ resistors and repeat the measurements in 5.
Check that no ADC saturates and obtain Vi and Vo as function of time.
Compare the ripple with its upper bound as calculated in 6.

It is not really true that the diode changes from two states ON and OFF. In reality, the diode has an exponential function and conducts some current whenever its V_D voltage is positive. It is apparent on the curves because the exponential OFF state curve is really seen only for V_D voltages much lower than the 0.7 V value associated to Vγ.

If you detect some discrepancies between the measurements and the calculations, consider only the part of the capacitor discharge curve after the cross between the Vi and Vo curves.

When the ripple voltage is low, the exponential curve of the capacitor voltage for the diode in OFF state can be simplified using the first order Taylor approximation of the exponential.

$$V_L(t) = V_{L\,max} \cdot e^{-t/\tau} \approx V_{L\,max}\left(1 - \frac{t}{\tau}\right)$$

In this case the ripple can be easily calculated:

$$V_{L\,min} \approx V_{L\,max}\left(1-\frac{T}{\tau}\right)$$

$$\Delta V_{L\,max} = V_{L\,max}\left(1-1+\frac{T}{\tau}\right) = V_{L\,max}\,\frac{T}{\tau}$$

This is the formula usually used in power supply designs as, in this case, ripple is specified to be small.

	9	Use the above formula to obtain an approximation of the ripple we will get in the 8 measurement. Compare it to the exact exponential measurement.

Demodulating a signal

As said at the start of the document, obtaining a DC voltage from a sine wave is only one of the main uses of a rectifier circuit. Other of important usages of a rectifier is building amplitude demodulators.

In order to work this subject we will first create an amplitude modulated signal (AM). The characteristics of this signal are:

- Carrier frequency of 500 Hz
- Modulating signal of 10 Hz (1/50 of the carrier)
- Voltage range of ±2 V in bridge mode
- 50% modulation depth

The modulation depth parameter means that the modulating signal changes a 50% of the carrier amplitude. In order to generate the signal we first import the **numpy** module and create a 1000 points array. The modulated low frequency signal will have this number of data points.

```
>>> import numpy as np
>>> x=np.arange(0,1000)
```

Then we define the angular frequencies relative to this array. As the modulating signal has 1000 points, its period must be 1000 points of X. As the carrier has a frequency 50 times the modulating signal, its period should be 20 points of X.

```
>>> wc=2*np.pi/20
>>> wm=2*np.pi/1000
```

Then we can compose the modulated signal multiplying the carrier with a signal that goes from 0.5 to 1.0 at the modulating signal frequency. After generating the signal we will show it on screen.

```
>>> s=np.sin(wc*x)*(0.75+0.25*np.sin(wm*x))
>>> slab.plot11(x,s)
```

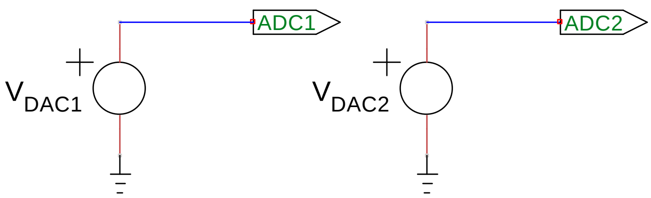
So far so good. Now we need to generate the ±2 V signals in bridge mode. We will show the also but you will need to zoom in to see the details.

```
>>> v1=1.1+s
>>> v2=1.1-s
>>> slab.plot1n(x,[v1,v2])
```

Afterwards we will send those signals to the hardware board and set the frequency. As the full table is one cycle of the modulating signal, its frequency will be 10 Hz.

```
>>> slab.loadWavetable(v1)
>>> slab.loadWavetable(v2,second=True)
>>> slab.setWaveFrequency(10)
```

Now we can check that the generating of the modulated signal is correct. Just connect DAC 1 to ADC 1 and DAC 2 to ADC 2.



And then execute the following code to show two full cycles of the modulation signal (2000 data points):

```
>>> slab.tranStore(2000,2)
>>> t,a1,a2=slab.wavePlot(dual=True,returnData=True)
```

As we work in bridge mode we can obtain the input signal as:

```
>>> vi=a1-a2
>>> slab.plot11(t,vi,"","time (s)","Vi (V)")
```

🛠	**10**	Check that you are able to generate the modulated signal. Check that both the amplitude, the modulation depth and the frequency are correct.

In order to demodulate the signal we will use the same circuit measured in 🛠5 but we will need to change the component values to set a proper τ value. Basically we want the output of the rectifier to follow the 10 Hz signal envelope. If τ is too low the output will follow the full signal, not the envelope. If τ is too high, we will only get the maximum of the signal.

The maximum slope of the 10 Hz modulating signal is:

$$\left.\frac{\partial Vm}{\partial t}\right|_{max} = 0.5V \cdot \omega_m$$

We can make this slope to coincide with the ripple:

$$\frac{\Delta V_{L\,max}}{T} = \frac{V_{L\,max}}{\tau} = 0.5V \cdot \omega_m$$

From that we can determine t, and, if we fix C_F to be 10 μF, we can obtain R_L. Remember that R_L is divided in two resistors R_{L1} and R_{L2}. In our case our modulating signal is a constant tone. In practice there will be a frequency range for the modulating signal and we will need to obtain a compromise value of τ.

📋	**11**	Determine the limit value of R_{L1} and R_{L2}. Choose the resistors values that are below that value.

Now we need to change the resistor values on the circuit and proceed with the demodulation measurements.

```
>>> t,a1,a2,a3=slab.wavePlot(dual=True,returnData=True)
>>> vi=a1-a2
>>> vo=(a3-a2)*2
>>> slab.plot1n(t,[vi,vo],"","time (s)","Vi,Vo (V)")
```

🛠	**12**	Measure the demodulator response to check that it operates as expected.

The demodulated signal perhaps is not perfect, but its shape should be similar to the expected one.

In simple receiver designs, the rectifier does not bother using any capacitor. Try to remove the capacitor from the circuit an repeat the measurements:

```
>>> t,a1,a2,a3=slab.wavePlot(dual=True,returnData=True)
>>> vi=a1-a2
>>> vo=(a3-a2)*2
>>> slab.plot1n(t,[vi,vo],"","time (s)","Vi,Vo (V)")
```

You can better see the output if you see it alone:

```
>>> slab.plot11(t,vo,"","time (s)","Vo (V)")
```

As the receiver audio amplifier, together with the speaker, has usually an inherent bandwidth limitation, you can let the bandwidth to restore the modulating signal from the rectified Vo signal.

Adding some signal processing

We can filter the signal ourselves to see the effect of the bandwidth. This section deals with the FIR filtering capabilities of the **scipy.signal** package. You don't need to understand the theory of FIR filters to use them in this project as the exact commands to obtain the desired results will be provided.

The modulating signal we are generating has a 10 Hz frequency and 1000 data points, so the sampling frequency is 10 kHz and the Nyquist frequency is 5 kHz. The carrier frequency is 500 Hz so we can just filter all frequencies below 50 Hz. In order to do that we can generate a 100 tap low pass filter with a 50 Hz cutoff frequency using the ***firwin*** function on the **scipy.signal** module.

```
>>> import scipy.signal as signal
>>> taps = signal.firwin(100,50,pass_zero=True,nyq=5000)
```

Once we have the filter, we can apply it to the rectified signal we have previously obtained and show in a graph both the rectified signal and the filter output.

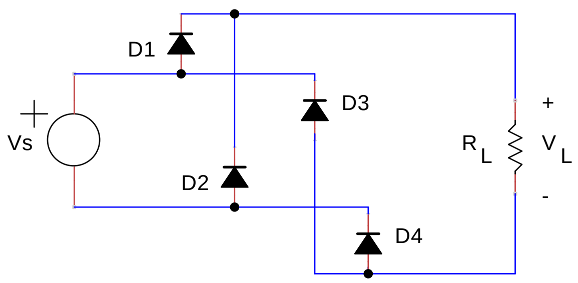
```
>>> vof = scipy.signal.lfilter(taps,1.0,vo)
>>> slab.plot1n(t,[vo,vof],"","time (s)","Vo,Vof (V)")
```

You can see that, after a start transient, the output of the filter extracts the shape of the modulating signal from the rectified one. Note that the signal has a better shape that the one we obtained by adding a capacitor in parallel with the load resistance.

🛠	**13**	Remove the C_F to obtain the non filtered rectified signal. Filter the signal to recover the modulating signal.

Full wave bridge rectifier

Up to this point we have worked with the basic single diode rectifier. The main drawback of this rectifier is that it only let pass the positive part of the input signal, so we don't get any energy or information from the negative part of the signal. The following circuit, that uses four diodes instead of one, is the **full wave bridge rectifier**. It is called **full wave** because it uses information not only from the positive part of the input wave but also from the negative part. It is called **bridge** because the output has a different reference than the input and is located, between two symmetric subcircuits.



In order to solve this circuit we could use the same technique used for the basic rectifier in 1 and 2. This time, as we have four diodes and each one could be in two states (ON, OFF), the number of combined hypothesis grow to 2^4=16 possibilities. Testing all of them would be too much.

Fortunately, not all hypotheses are possible. In fact only three are possible and we can work out which they are from the circuit. Let's start seeing that all the circuit connected to Vs is passive and resistive. That is, no element is able to store or generate energy.

That means that if Vs is positive, current must go out of it from the (+) terminal and return to the (-) terminal. Current going out of the Vs (+) terminal reaches D1 and D3, but as D1 is blocking, it can only go to D1, as the current goes through R_L, from the positive to the negative terminal, voltage drops before reaching D2 and D4. Both diodes are in the correct orientation but current cannot go through D3 because that would mean going from a lower voltage to a higher voltage and no passive component can do that. That means that current returns to Vs through diode D4.

In a similar way, if Vs is negative, current exits the source from the (-) terminal and goes through D2, R_L and D3 before returning to the source on the (+) terminal. As the current always enters the load on its (+) terminal, voltage on the load is always positive.

There is another case left when voltage in the source is not enough to turn the two diodes in the current path. In this case no diode conducts.

The following table shows all three cases:

Case	D1	D2	D3	D4	Comments
#1	ON	OFF	OFF	ON	Vs positive, current exits Vs from (+)
#2	OFF	ON	ON	OFF	Vs negative, current exits Vs from (-)
#3	OFF	OFF	OFF	OFF	Current is zero

For each case we can set the voltage or current equation. The case will be possible for the Vs range of values that make true all the four inequations for each diode state.

14

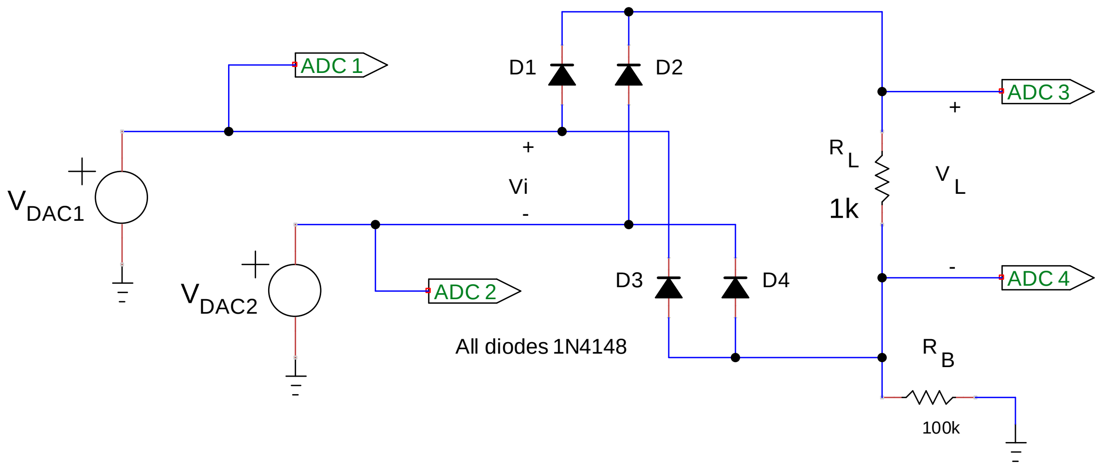
Solve the circuit obtaining $V_L(V_S)$ for all three cases.

Determine the V_S range compatible with each case.

Draw the $V_L(V_S)$ response for V_S values between -3 V and 3 V. Consider a 0.7 V value for $V\gamma$ on the diodes.

You should obtain a three region "V" shaped drawing, with a flat center region, for the $V_L(V_S)$ response.

Now, it is time to measure the circuit. The following figure shows the circuit with all connections.



Observe the 100 kΩ bias R_B resistor. We don't need this resistor for the circuit to work. It will work ok regardless of having this resistor or not. The problem is measuring the circuit, not making it work.

In State #3, all diodes are in OFF state. That means that the load R_L will be isolated from the DACs. All ADC measurements need to have a DC path to ground because the V_L measurement is not intrinsically deferential. We measure ADC 3 and ADC 4 respect to ground and compute V_L from the difference.

The bias resistor R_B provides the needed DC path to ground when all diodes are in OFF state. Sometimes you could get good measurements without this resistor but don't count on it.

Build the above circuit and obtain the DC Input to Output curve.

```
>>> dc.curveVVbridge(3,3)
```

🛠	**15**	Measure circuit to obtain the DC response curve. Compare it from the one calculated in 14. Measure again removing the 100 kΩ R_B resistor. What do you observe?

After the DC measurements we can repeat the AC ones. We will set the two DAC waves between 0.1 V and 3 V.

```
>>> slab.waveSine(0.1,3.1,100)
>>> slab.setWaveFrequency(50)
>>> slab.waveSine(3.1,0.1,100,second=True)
```

Then perform the measurement for 5 full waves.

```
>>> slab.tranStore(500,4)
>>> t,a1,a2,a3,a4 = slab.wavePlot(dual=True, returnData=True)
```

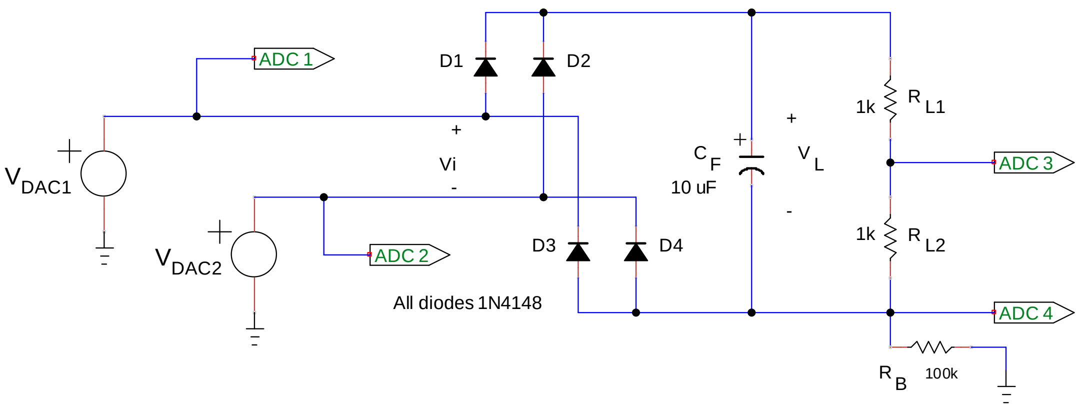
After checking that no ADC saturates we can obtain the input and output waveforms.

```
>>> vi = a1 - a2
>>> vo = a3 - a4
>>> slab.plot1n(t,[vi,vo],"","time (s)","Vi,Vo (V)")
```

🛠	**16**	Measure the response of the circuit against a sine wave. Compare the result with the one obtained on 🛠4.

Observe how the output features a larger drop from the input compared with the basic rectifier circuit. This is due to the fact that the current needs to get through two diodes instead of one.

We can also repeat the measurements when using a C_F filter capacitor.



Remember that we need to generate DAC signals with less range:

```
>>> slab.waveSine(0.1,2.1,100)
>>> slab.setWaveFrequency(50)
>>> slab.waveSine(2.1,0.1,100,second=True)
>>> slab.tranStore(500,4)
>>> t,a1,a2,a3,a4 = slab.wavePlot(dual=True, returnData=True)
```

After checking that no ADC saturates we can obtain the input and output waveforms.

```
>>> vi = a1 - a2
>>> vo = 2*(a3 - a4)
>>> slab.plot1n(t,[vi,vo],"","time (s)","Vi,Vo (V)")
```

🛠	**17**	Check the operation of the diode bridge with the C_F capacitor. Compare the ripple with the one on the 🛠5 measurements.

The ripple should be lower than the one on the base rectifier because the capacitor lost charge is replaced every half period not each period.
When the ripple is low enough to substitute the exponential with its Taylor approximation, it can be calculated as:

$$\Delta V_{L\,max} = V_{L\,max} \frac{T}{2 \cdot \tau}$$

Last comments

In this project we have dealt with two rectifier topologies: the basic half wave rectifier and the full wave bridge rectifier. We have seen applications both for obtaining a DC voltage from an AC sine voltage and for demodulating an AM signal. Although those two applications are very important, the diodes can be used for many other applications.

One important subject in this document is the electronics **bridge** concept. It is important to understand it because it can be used in a lot of applications. Bridges are used to inject a signal to a circuit, as in the bridged DAC configuration we have used in the measurements or in the diode bridge, but they can also be used to perform measurements like in the Wheatstone bridge.
In the SLab system we will use the bridge both to provide positive and negative excitations to a circuit from an unipolar supply and to broaden the voltage range.

Finally, in this document we have dealt also with the need for a DC path to ground when we perform floating differential measurements. Most measurement instruments require a DC path from the measured node to the instrument ground reference and this fact is easy to be overlooked if you perform a differential measurement by subtracting two ground referenced measurements.

References

SLab Python References

Those are the reference documents for the SLab Python modules. They describe the commands that can be carried out after importing each module.

They should be available in the **SLab/Doc** folder.

TinyCad

Circuit images on this document have been drawn using the free software TinyCad https://sourceforge.net/projects/tinycad/

SciPy

All the functions plots have been generated using the Matplotlib SciPy package.

https://www.scipy.org/

LTSpice

Circuit simulator provided for free from Linear Technology. You can use the simulator to obtain numerical solutions of complex circuits.

http://www.linear.com/designtools/software/