EE 230
Experiment 8-9
Fall 2006

Applications of Comparators and Waveform Generators in Circuit Design

Objectives: The primary objective of this experiment is to investigate some applications of the comparator in useful circuit applications. A second objective will be to develop systematic design strategies that combine several circuits that have been investigated separately throughout this course. A third objective is to investigate waveform generators that can produce both square waves and sinusoidal waveforms.

Equipment:
Computer with SPICE, Signal Express, GP-IB capability, and appropriate IVI drivers
HP E3631A or equivalent power supply (GP-IB Capable)
HP 33120A or equivalent signal generator (GP-IB Capable)
HP 34401A or equivalent multimeter (GP-IB Capable)
HP 54602B or equivalent oscilloscope

Parts:
Assortment of Resistors and Capacitors
3 741 op amps
Potentiometer
Amplified speaker
2 Photoresistors
RED LED
Thermister

Practical Details: The comparator is one of the more widely used building blocks. It can be viewed as an analog to digital converter whereby an analog input signal is converter to a Boolean output variable that depends upon the value of the input. Sometimes comparators are designed to have a single comparison threshold and at other times a hysteresis loop is included as part of the comparator.

Some applications of comparators will first be discussed.

Noninverting Comparator with Hysteresis

Two noninverting comparators with hysteresis will be considered in this section. The edges of the hysteresis loop, the location of the hysteresis loop, and the width of the hysteresis loop all play key roles in circuits that use these comparators.

A noninverting comparator with Hysteresis is shown in Fig. 1.

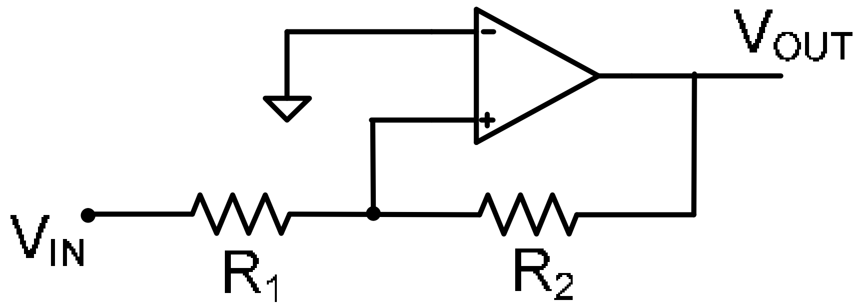


Fig. 1 Noninverting Comparator with Hysteresis

If V_{SS}=-V_{DD}, The edges of the hysteresis window are defined by the two equations

$$V_{HYH} = \frac{\theta}{1-\theta} V_{DD}$$

$$V_{HYL} = \frac{-\theta}{1-\theta} V_{DD}$$

where

$$\theta = \frac{R_1}{R_1 + R_2}$$

A modification of this circuit is shown in Fig. 2. The edges of the hysteresis region are now also dependent upon the voltage $V_{XX.}$

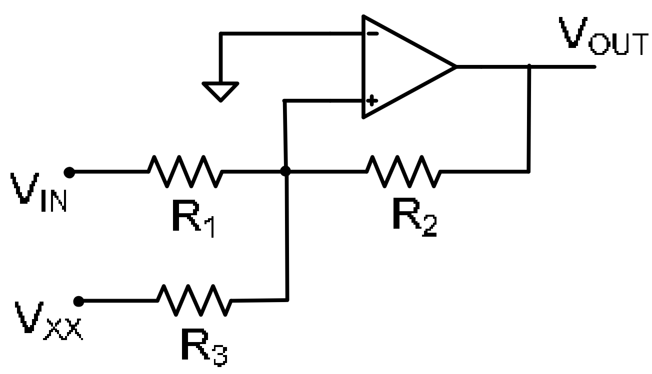


Fig. 2 Modified Comparator with Hysteresis

If the voltage V_{XX} were made time-varying, such as with a triangle waveform, the edges of the hysteresis loop would become time-varying as well.

A second modification of the comparator is shown in Fig. 3. In this modification two nonlinear devices (diodes) are shown. These devices can be modeled by the I-V relationship shown in Fig. 4. Although we have not studied diodes in the lecture, we have looked at nonlinear devices with I-V relationships that are actually those of a diode. The edges of the hysteresis region are also dependent upon the voltage V_{XX} and as with the previous circuit, if the voltage V_{XX} were made time-varying, such as with a triangle waveform, the edges of the hysteresis loop would become time-varying as well.

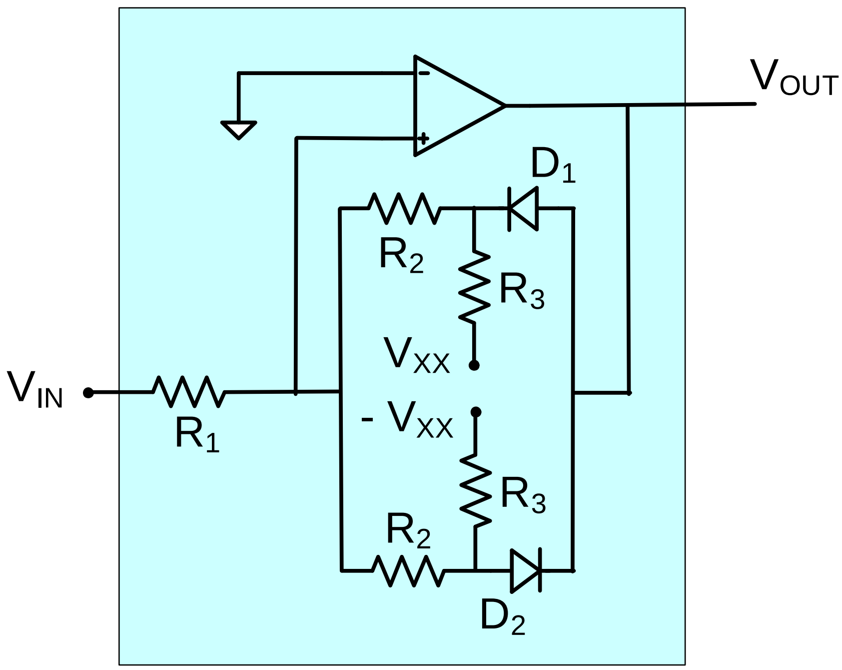
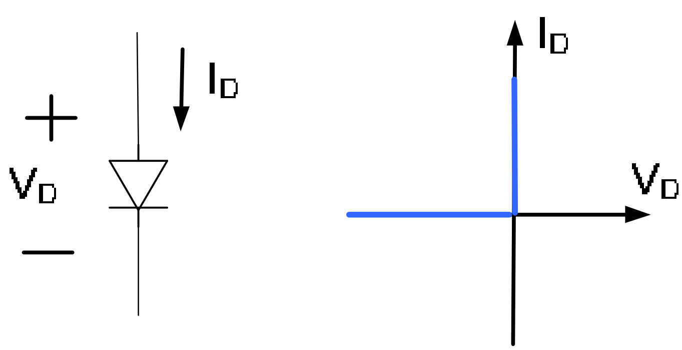


Fig. 3 Modified Comparator with Hysteresis



$I_D = 0 \quad \text{if } V_D \le 0$

$V_D = 0 \quad \text{if } I_D \ge 0$

Fig. 4 Transfer Characteristics of a Diode

Waveform Generator

A triangular and square waveform generator is shown in Fig. 5. In this circuit, the frequency of oscillation is determined by R, C, and the edges of the hysteresis loop.

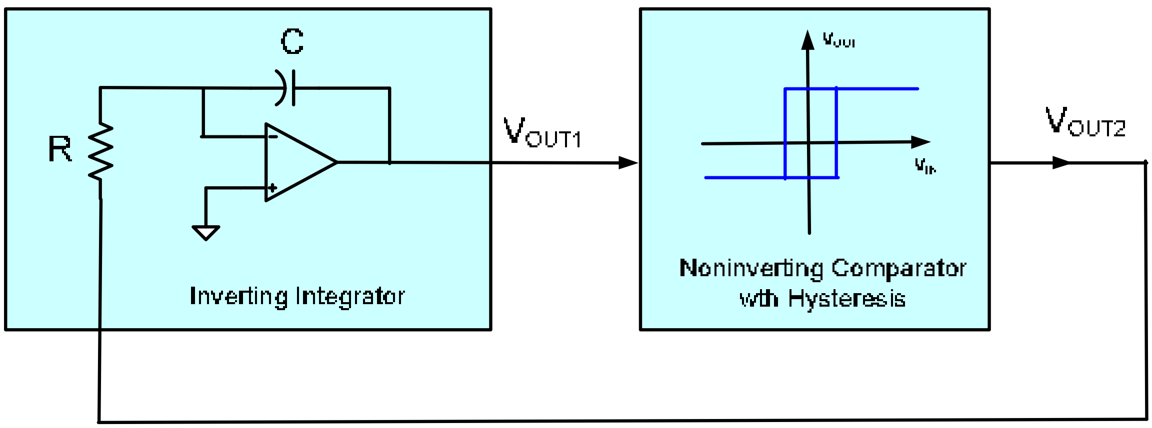


Fig. 5 Triangle and Square Waveform Generator

If V_{SATH}=V_{DD} and V_{SATL}= -V_{STATH} for the comparator (where V_{SATH} and V_{SATL} are the high and low saturation voltages of the comparator respectively), the frequency of oscillation is given by the expression

$$f=\frac{1}{2RC}\frac{V_{DD}}{\left(V_{HYH}-V_{HYL}\right)}$$

If the edges of the hysteresis window were made time-variable, the frequency of oscillation would be time-variable as well.

Noise in Amplifiers

The random movement of electrons in semiconductor devices causes random fluctuations in the currents flowing in the devices. This random fluctuation is termed device noise or, simply, noise. Since an operational amplifier is made of a large number of devices, all of which are noisy, the operational amplifier will exhibit noise in its output as well. This noise can be represented by equivalent noise sources referred to the input much as the offset voltage can be represented by an equivalent dc source at the input. In many cases, this noise can be approximated by the model shown in Fig. 6. where Vn is a noise voltage source. We will not go into details about characterizing Vn in this course beyond the statement that it is comprised of noise at many different frequencies and, in a frequency band, can be represented by an equivalent RMS voltage. If the op amp is used to build a high-gain amplifier, the noise voltage is amplified as well.

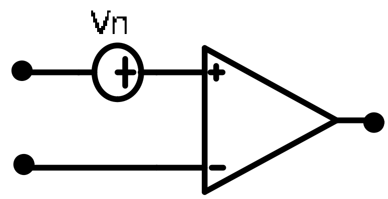


Fig. 6 Input Referred Noise Voltage of Op Amp

Generally the noise associated with an op amp is undesirable but, on occasion, there is a need for a noise source. The circuit of Fig.7 will serve as a noise voltage source. The noise can be increased by increasing the gain of the circuit or by cascading two or more stages to amplify the noise. A capacitor C can be added to the amplifier as shown in Fig. 8 to prevent the offset voltage from causing the output of the amplifier to saturate from the input offset voltage if the gain is too high. The capacitor actually results in filtering the noise with a high-pass filter. If used as a noise generator, the capacitor should be chosen so the pole of the filter is below the desired noise band.

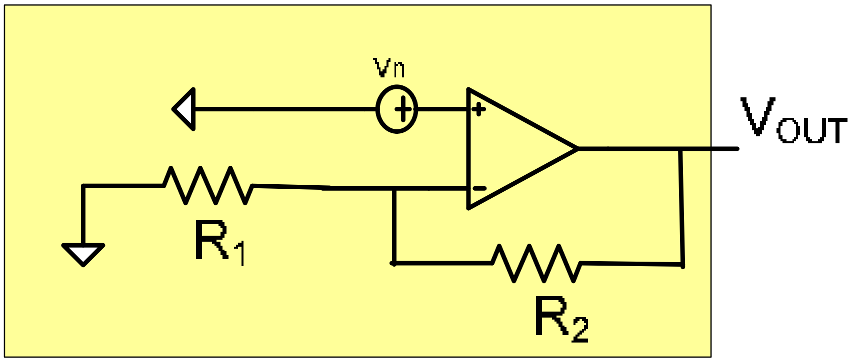


Fig. 7 Op-Amp Based Noise Generator

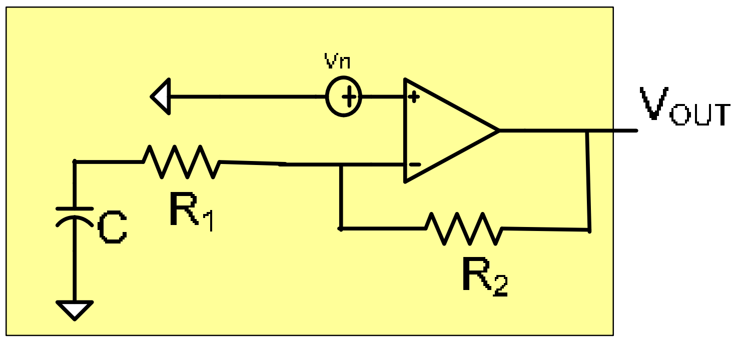


Fig. 8 Op-Amp Based Noise Generator with Offset Voltage Compensation

LED Indicators

Light-emitting diodes are often used as indicator lamps. Although we have not discussed the models for Light-emitting diodes, the circuit shown in Fig. 9 will turn on the LED in your parts kit if the voltage V_X is about 30V and it will turn it off if V_X is about 0V. The resistor is used to limit the current flowing in the device.

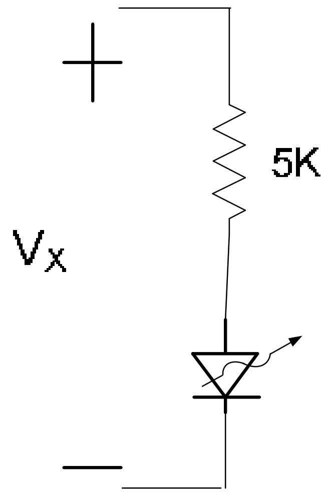


Fig. 9 LED-Based Indicator

Sinusoidal Oscillators

A sinusoidal oscillator requires exactly one pair of complex conjugate poles on the imaginary axis and no poles in the RHP. The circuit shown in Fig. 10 can be used to place a pair of poles on the imaginary axis if the dc gain of noninverting amplifier is appropriately chosen.   If all components are ideal, a gain of 3 is required to create the pair of imaginary axis poles but if components are not perfectly matched or if nonideal characteristics of the op amp are considered, the required gain will differ a little from the ideal value of 3. . This circuit is termed a Wein-Bridge oscillator and if the poles are placed on the imaginary axis, the frequency of oscillation is $\omega_{OSC}=1/RC$.

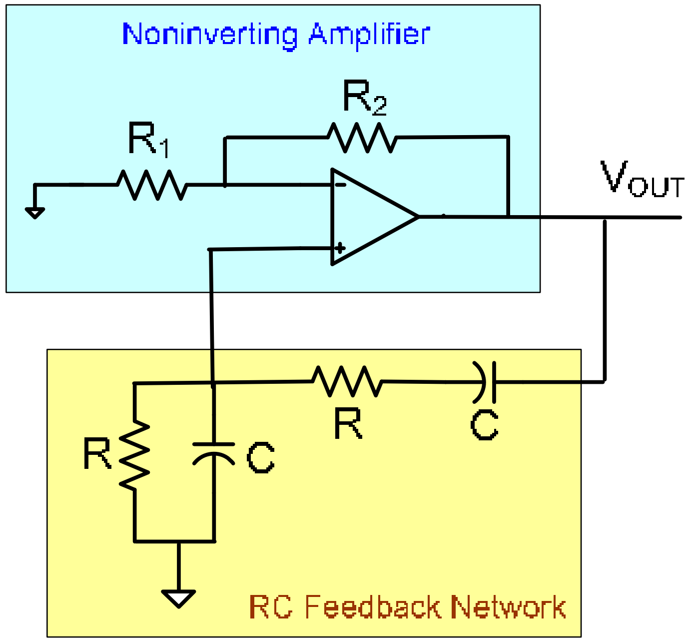


Fig. 10 Wein-Bridge Oscillator

Practically, the poles are placed slightly into the RHP to guarantee oscillation will be sustained in the presence of component variations and other nonidealities in the circuit. This is achieved by making the gain of the noninverting amplifier a little larger than 3. As such, the amplitude of the output will start to grow and ultimately be limited by the nonlinearities inherent in the amplifier. The transfer characteristics of the amplifier including the saturation limits are shown in Fig. 11 and it is the saturating nonlinearities that limit the amplitude of the output waveform of the oscillator. Unfortunately this type of abrupt change in amplifier gain at the transition points denoted by the circles in the figure cause rather significant distortion in the output waveform of the oscillator.

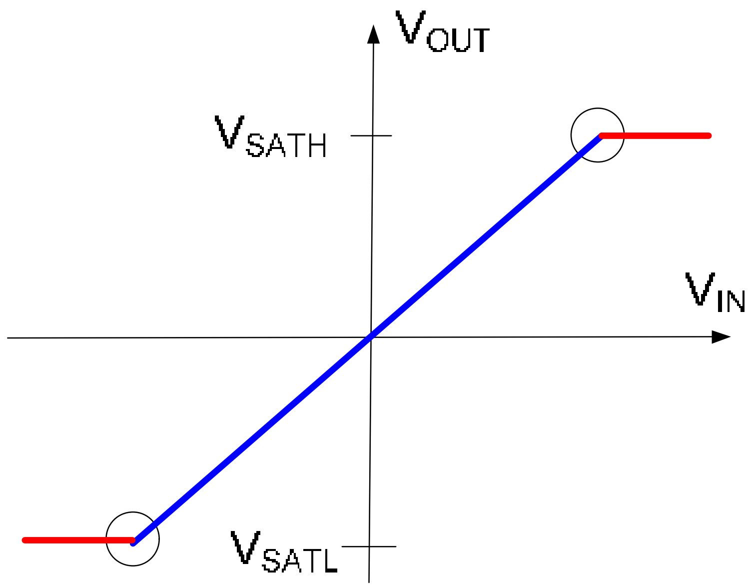


Fig. 11 Transfer Characteristics of Noninverting Amplifier Showing Saturating Nonlinearities

A significant reduction in distortion in the oscillator can be obtained if a less abrupt change in the gain of the amplifier is used.

Amplifiers with nonlinear transfer characteristics

The amplifier shown in Fig. 12 using the nonlinear device of Fig. 4 has a nonlinear transfer characteristic with a change in gain that occurs at V_{IN}=0. This is depicted in Fig. 13 and if the saturation limits are neglected, V_{OUT} is given mathematically by the expression

$$V_{OUT} = \begin{cases} 1+\dfrac{R_2}{R_1} & V_{IN} \le 0 \\ 1+\dfrac{R_2//R_3}{R_1} & V_{IN} > 0 \end{cases}$$

The nonlinear device causes the change in gain at V_{IN}=0. A diode can be used for the nonlinear device and has a transfer characteristic similar to that shown in Fig. 4.

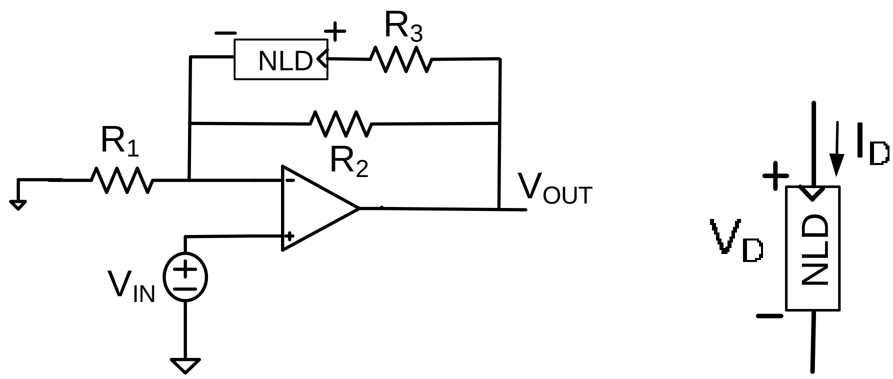


Fig. 12 Amplifier with nonlinear transfer characteristic

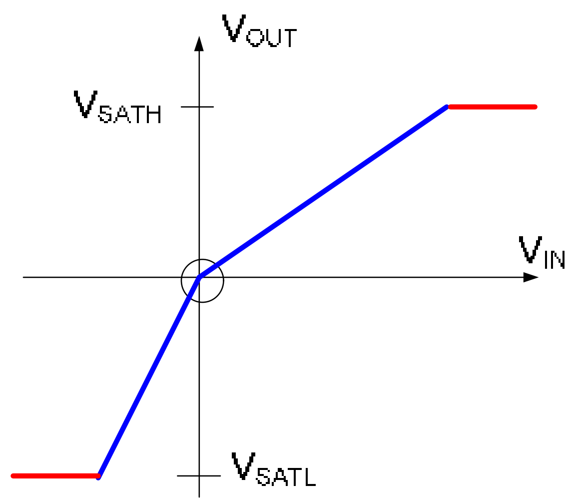


Fig. 13 Amplifier with less abrupt change in slope at $V_{IN}=0$

Although this circuit does provide for a less abrupt change in slope, it is not symmetric and as such would cause distortion if used for the amplifier in the Wein-Bridge Oscillator.

An amplifier circuit that provides a symmetric nonlinear transfer characteristic is shown in Fig. 14.

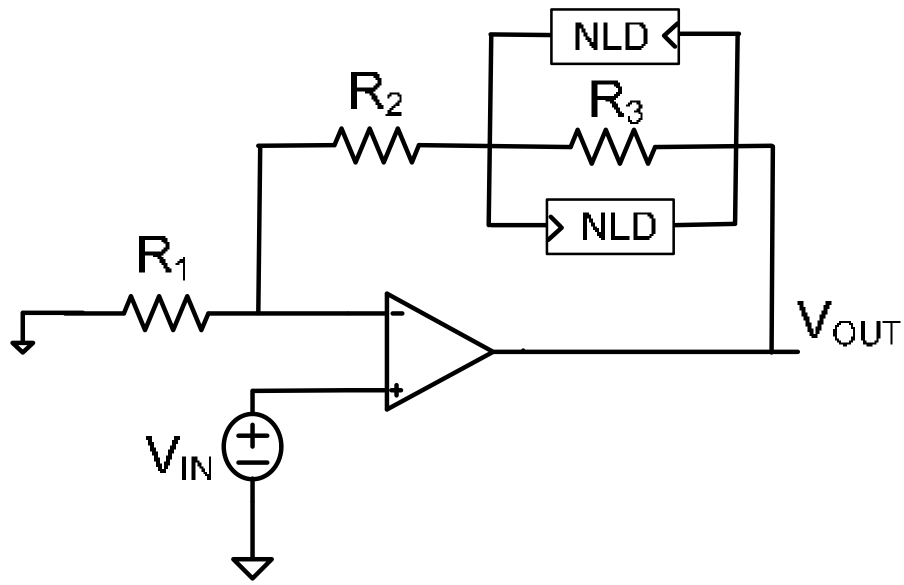


Fig. 14 Amplifier with Symmetric Transfer Characteristics

If the NLD (note the orientation of the two NLDs are different) has the transfer characteristic

$$\begin{array}{ll} I_D = 0 & \text{if} \quad V_D \le V_{XX} \\ V_D = V_{XX} & \text{if} \quad I_D > 0 \end{array}$$

and shown graphically in Fig. 15 and if the saturation limits of the op amp are neglected, it can be shown that the amplifier of Fig. 14 will have the transfer characteristics given by the expression

$$V_{OUT} = \begin{cases} \left(1+\dfrac{R_2}{R_1}\right)V_{IN} + V_{XX} & V_{IN} > V_{XX}\dfrac{R_1}{R_3} \\ \left(1+\dfrac{(R_2+R_3)}{R_1}\right)V_{IN} & -V_{XX}\dfrac{R_1}{R_3} \le V_{IN} \le V_{XX}\dfrac{R_1}{R_3} \\ \left(1+\dfrac{R_2}{R_1}\right)V_{IN} - V_{XX} & V_{IN} < -V_{XX}\dfrac{R_1}{R_3} \end{cases}$$

This is shown along with the saturation limits graphically in Fig. 16. Note that the nonlinear transfer characteristic shown in Fig. 15 differs from that of Fig. 4 by a shift in the discontinuity from V_D=0 to V_D=V_{XX}. Actually, silicon diodes are better approximated by the nonlinear transfer characteristic of Fig. 15 where the voltage V_{XX} is approximately 0.6V. As such, silicon diodes can be used for the NLDs in the amplifier of Fig. 14.

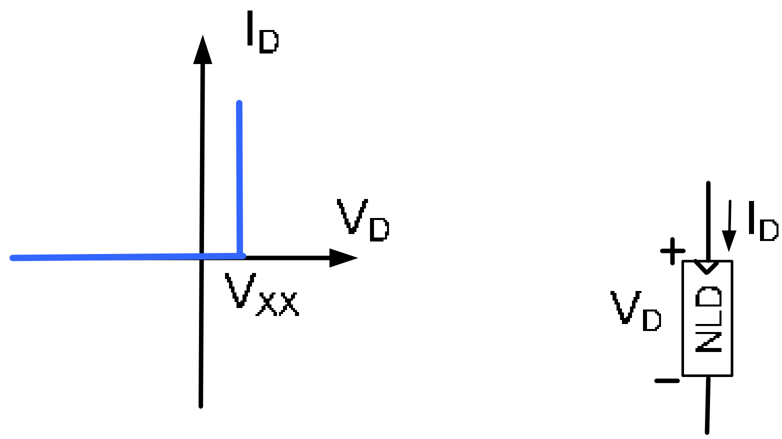


Fig. 15 Transfer Characteristics of a NLD

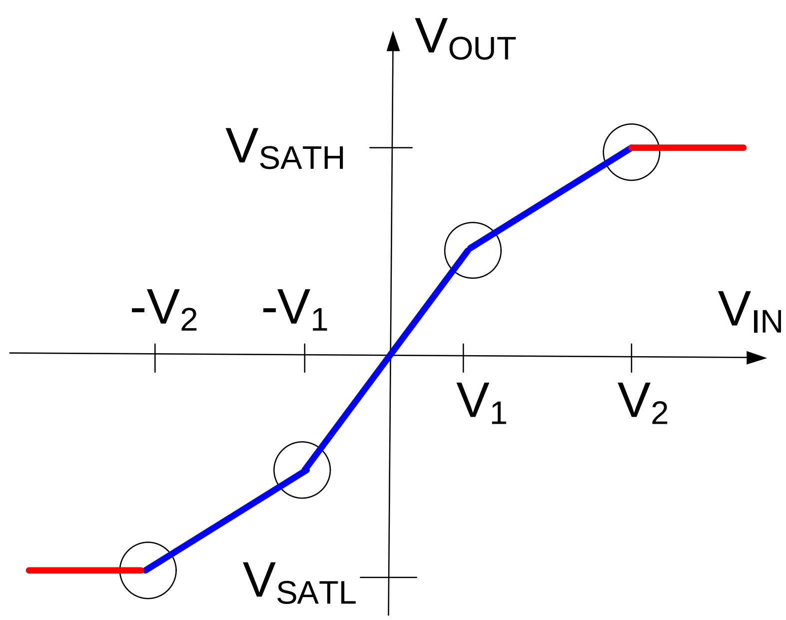


Fig. 16 Transfer characteristics of amplifier of Fig. 14

Part 1 Comparators with Voltage Controlled Hysteresis

1) Design and test the two comparators discussed above that have a hysteresis loop that can be controlled by a dc control voltage. Compare theoretical and experimental performance of these comparators.

2) In one of these comparators the width of the hysteresis loop can be changed by changing the control voltage. Test this comparator by using a triangle wave generator to change the width of the hysteresis loop. Use a relatively low frequency for the triangle wave generator (e.g. 1Hz or lower).

Part 2 Build a Noise Voltage Generator

1) Design and noise voltage generator that has an output voltage that is around 2V RMS. We do not have a good procedure for measuring the output voltage but if the waveform, when viewed on the scope, is mostly below 2V but bounces above 3V on occasion you will have a signal that is close to 2V.
2) Listen to the noise source on a speaker and comment about how the noise signal "sounds" relative to the periodic signals that were considered previously.

Part 3 Thermistor-based thermostat

a) Build a thermistor-based temperature sensor that will provide an output voltage on the output terminal of an op amp that is 5V when the temperature is approximately 90^oF. Give an approximate plot of the transfer characteristics of your temperature sensor (Vo vs T) for temperatures in the range of 70^oF to 110^oF.
b) Design a thermistor-based thermostat using the temperature sensor designed in Part a) that will turn on a RED LED if the is above approximately 90^oF and turn the LED off if it is below 90^oF. What do you observe if you try to hold the temperature around 90^oF?
c) Build a summer that will add a noise voltage of about 50mV to the output of the temperature sensor and now put this signal into your temperature sensor. How does the performance change?
d) Add a hysteresis loop to your thermostat that is approximately 5^oF wide. How does the circuit now perform both with and without the noise source? Be sure to include a theoretical analysis at how you sized the components in your thermostat.

Part 4 Design a "Siren"

Design a circuit that has a frequency of oscillation that can be changed with a dc voltage (that varies between -1V and +1V) between 400Hz to 800Hz. First test this waveform generator with a triangle waveform generated by the function generator and then test this waveform generator by generating your own triangle waveform. Be sure to include a theoretical analysis that supports your design. Demonstrate this "Siren" with a speaker as well.

Part 5 Nonlinear Amplifier

Design and test a nonlinear amplifier that has a gain of +10 for $V_{IN}<0$ and of +2 for $V_{IN}\geq 0$. At a minimum, the test should provide the transfer characeristics and the output waveform for a sinusoidal excitation. Include a comparison of theoretical and experimental performance.

Part 6 Wein-Bridge Oscillator

Design and test a Wein-Bridge Oscillator that oscillates at a frequency of approximately 2KHz. Initially use only a finite gain amplifier and let the nonlinearities of the amplifier limit the signal amplitude. Then include a more gentle amplitude limiting circuit such at the symmetric nonlinear amplifier of Fig. 14. Comment on how the distortion compares in the two implementations.