Operational Amplifier Based Hysteresis Circuits

Appendix A contains the mathematics and the theory for a hysteresis circuit. However just knowing the theory doesn't make the circuit work properly, in many cases because of issues in basic design the performance of a hysteresis circuit is significantly compromised. In such designs the calculated parameters for a hysteresis circuit won't match actual circuit measurements or even work.

A successful hysteresis circuit must have a solid reference point value of such low impedance that the hysteresis circuit op-amp's positive (+) input is fixed through an input resistor, and scales through a feedback resistor to the op-amp's output. The junction of these two resistors snap between two voltage values. The difference of these two voltage values equals the calculated hysteresis in equation below…

$$\text{Hysteresis} = [R^{Input} / (R^{Input} + R^{Feedback})] * [(V^{OutSat+}) - (-V^{OutSat-})]$$

Single Voltage Power Supply Hysteresis Circuits

For most single supply applications of V^{SS+} = 5V, 6V, 12V and 15V single power supplies the above hysteresis equation may be simplified to…

$$\text{Hysteresis} = [R^{Input} / (R^{Input} + R^{Feedback})] * (V^{ss+} - .7V)$$

Note: The negative $V^{OutSat-}$ is zero in single supply circuit applications.

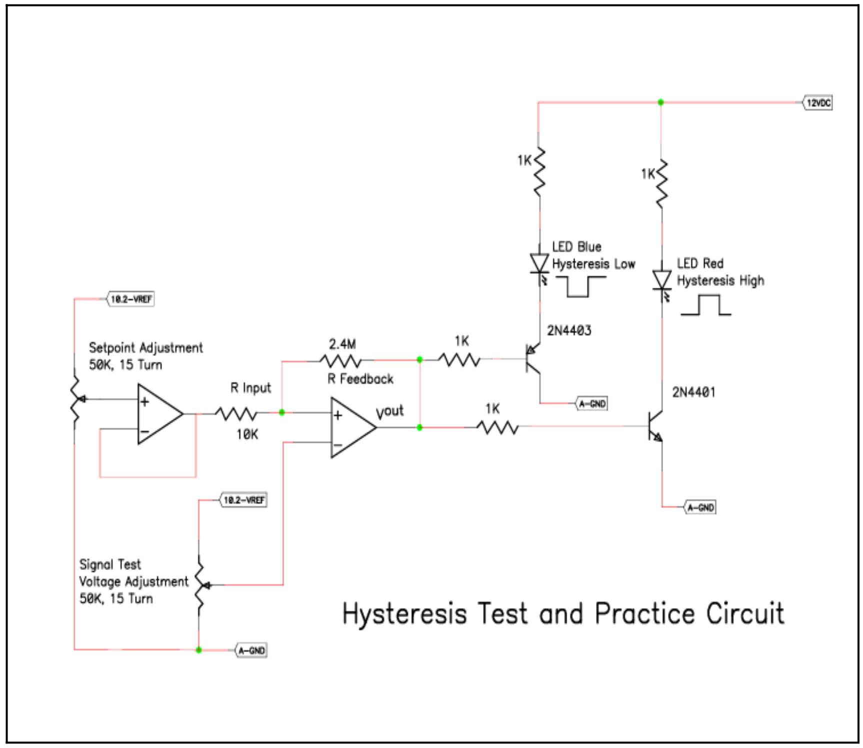
Dual Voltage Power Supply Hysteresis Circuits

For most single supply applications of V^{SS+} = 5V, 6V, 12V, 15V & V^{SS-} = -5V, -6V, -12V, -15V power supplies the above hysteresis equation may be simplified to…

$$\text{Hysteresis} = [R^{Input} / (R^{Input} + R^{Feedback})] * [2 * (V^{ss+} - .7V)]$$

Note: This only works for symmetrical +/- supplies powering the hysteresis op-amp.

Example 1, Single Supply Hysteresis



Our test circuit shown is a basic Hysteresis circuit using one operational amplifier (linear Technologies 1013/1014), two variable voltage sources, and two output LED's driven by basic transistors.

This circuit is powered by a single ended supply +12V to Analog Ground. We are now ready for some calculations, validation and analysis…

Test equipment used is a Fluke digital voltmeter, we need accuracy down to one mV. All voltage references are to analog ground.

We will go through a few basic steps in our practice and analysis.

Step-1; Adjust the voltage to the positive op-amp input resistor to 3.500 Vdc. This input will be our voltage reference for the base Hysteresis calculation and subsequent experiments. This voltage will be the central voltage for our circuit. The LT1013/1014 op-amp has a saturation rail voltage of approximately (V^{ss+} - .7 Vdc), in these calculations 11.3Vdc is used for $V^{OutSat+}$. It is important to remember that our resistor value tolerances are /- 5% when comparing calculated to measured values.

Step-2; By increasing and decreasing the test voltage entering the op-amps inverting input. We will see the LED's change color between an on and off state. Using our formula above we use, the 10000 ohm input resistor, 2.4 Mohm positive feedback resistor and 11.3V for our saturation voltage. Using the formula [10,000Ω / (10,000Ω + 2.4E6Ω)] * 11.3V our hysteresis calculates to 46mV. Our hysteresis mid point is our 3.500 Vdc voltage of our set-point, so when we are between 23mV above and 23mV below our set point voltage, our circuit remains in a fixed memory state and our output is stable, based on the last threshold crossed. When we go more than 23mV (3.523V) above our set-point, our circuit will be turned off (blue LED lit), when we go less than 23mV (3.477V) below our set-point, our circuit output turns on (red LED is lit).

Step-3; Adjust the test voltage* down until the red LED is lit, if the red LED is already lit, no action is necessary.

a) a. slowly increase the test voltage* until the blue LED becomes lit.
b) b. record the voltage, this is the hysteresis upper voltage threshold.
c) c. slowly decrease the test voltage* until the red LED becomes lit.
d) d. record the voltage, this is the lower hysteresis voltage threshold.

Step-4; Verify the difference between these two voltage values is +/- 5% of 46mV.

Step-5; Verify the positive junction voltage in the Hysteresis circuit.

a) place a voltmeter between analog ground, and the positive input pin of the LT1013/14 op-amp.
b) Adjust the test voltage* until the red LED is lit, this is the upper hold (memory) voltage of the circuit.
c) record the value.
d) Adjust the test voltage* until the blue LED is lit, this is the lower hold (memory) voltage
e) record the value

f) These two values the upper and lower hold values never change. This creates a snap threshold for the trip from high to low on the hysteresis circuit output eliminating analog transitions. The difference between these two values should be 46mV +/- 5%, +/- offset voltage of the op-amp. By using a LT1013/14 op amp input offsets are functionally zero. Older op-amps such as the LM741 and LM358 have much higher offsets and these limitations cause more variance in circuit measurements.

Step-6;

I would recommend testing different input set-points and becoming more familiar with hysteresis circuit performance. Additional steps would be to change the feedback resistor to 500Kohm, or 100Kohm. These resistor combination changes will give you great practice in understanding the math formulas, circuit design/applications and circuit validation.

Examples for you to test:

1. 10K, 100K resistor combination
   a) replace the feedback gain resistor in the previous circuit with 100K ohm resistor
   b) calculate a new hysteresis voltage, hysteresis = 1.03V
   c) perform previous tests, calculate results and compare with your measured results

2. 10K, 500K resistor combination
   a) replace the feedback gain resistor in the previous circuit with 100K ohm resistor
   b) calculate a new hysteresis voltage, hysteresis = 1.03V
   c) perform previous tests, calculate results and compare with your measured results

3. Try changing the following and test your calculated results with measured results
   a) replace the input resistor with other values from 5.1K to 100K
   b) change the set-point voltages and measure your predictions.
   c) Test further values of the feedback resistor, remember it must be >= input resistor.

Hysteresis circuits, observations, design considerations:

1. It is important to know the expected input signal noise, and input signal fluctuations, for any hysteresis circuit to function properly. The input signal must be limited to noise and signal fluctuations less than the voltage band of the hysteresis circuit. If the noise is larger than the hysteresis voltage value the hysteresis circuit will produce unexpected results.

   a) Example: A signal of a baseline voltage that fluctuates between 1 and 10 volts, with a superimposed random noise level of 70mV, enters a hysteresis circuit with a hysteresis band of 47mV. Since our random noise exceeds the hysteresis voltage, the hysteresis circuit will trigger on/off rapidly at the hysteresis thresholds. In this case the hysteresis circuit is useless. Circuit remedy options include:

      1. Widen the hysteresis voltage by at least 1.5x the expected noise. Increase the hysteresis value to 130mV to accommodate the expected input noise.
      2. Filter the noise from the signal using a low pass filter, or op-amp integrator.
      3. Amplify the signal with a noise filter, then lower the signal through divider resistors to improve the signal to noise ratio below the hysteresis voltage.

2. It is important to have a very stable hysteresis set-point voltage. Signal noise fluctuations in set-point voltage will cause a much wider variance in your measurements and they will most likely not match predicted calculations.

3. A few considerations must be made for the input resistor. The input resistor must be less than or equal to the positive feedback resistor. If the feedback resistor is too low in value the hysteresis circuit will not be able to switch between output states. The lowest input resistance value certain to work is around 5K, values lower

than this make it difficult for the positive feedback to reliably turn on/off the voltage of the setpoint at the op-amps positive input junction.

4. True analog comparitors such as the LM393 or similar have significantly faster output saturation switching times. However because of the lack of drive in the positive output direction for saturation, more hardware and design is necessary. You will need a pull-up resistor and an output buffer to your control electronics for these comparitors to be utilized.