Nonlinear Circuits - Comparators

Comparators represent a class of circuits that are basically nonlinear in operation. Comparators are used in analog-to-digital conversion, in oscillators and waveform generation applications.

Virtually all circuits considered so far have been linear. Linearity is achieved by:

- using negative feedback to force op amp to operate within its linear region and
- implementing the feedback network with linear elements.

A high gain amplifier with no feedback or with positive feedback causes the device to operate primarily in saturation at two discrete output levels ($+V_{Sat}$ and $-V_{Sat}$ for op-amps). This bistable behavior is the basis of voltage comparators and Schmidt-trigger circuits. Nonlinear behavior can be achieved by implementing the feedback network with nonlinear elements: such as diodes, analog switches and BJTs. Common examples are: precision rectifiers, peak detectors, sample and hold amplifiers, logarithmic amplifiers and multiplicators.

Voltage Comparators

The voltage comparator compares the voltage at one input v_P against the voltage at the other input v_N and outputs either a low voltage V_{OL} or a high voltage V_{OH}:

- $v_O = V_{OL}$ for $v_P < v_N$ or $v_{iD} < 0$,
- $v_O = V_{OH}$ for $v_P > v_N$ or $v_{iD} > 0$,

where $v_{iD} = v_P - v_N$ is the differential input. The input voltages v_P / v_N are analog (they can assume a continuum of values) and the output is a binary voltage (because it can assume only 2 values V_{OH} / V_{OL}). The comparator symbol and transfer function are shown in the next figure.

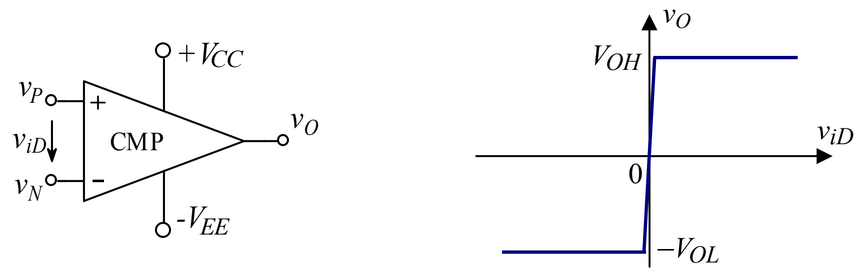

Figure – *The voltage comparator and its transfer function*

The Response Time

Comparator speed is characterized in terms of response time t_{PD}, also called propagation delay. The circuit for t_{PD} measurement and the time response are shown in the next figure. V_{OD} is input overdrive (excess voltage), with typical values of 1 mV, 2 mV or 10 mV. Depending on the device and overdrive voltage t_{PD} can range from few ns to few μs.

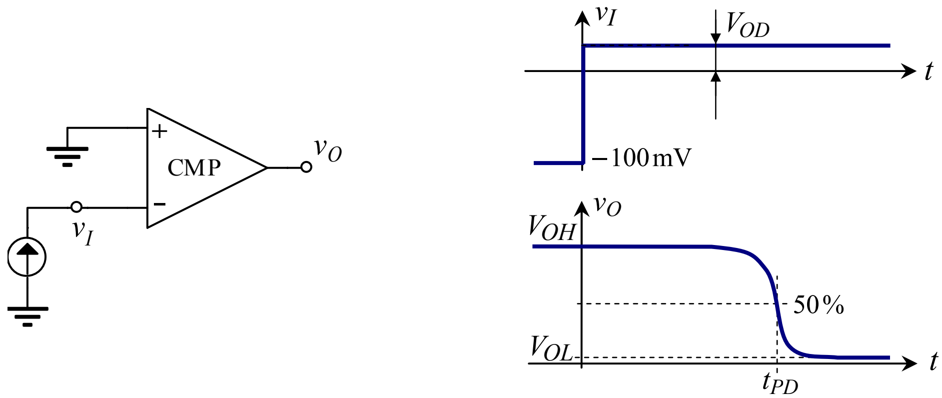

Figure – *The setup time for comparators*

The Op-Amps as Voltage Comparators

Op-amp can be used as comparators when speed is not critical. The example given in the next figure compares v_I against the threshold voltage V_T. The transfer function can be described by equations:

- $v_O = -V_{Sat}$ for $v_I < v_T$,
- $v_O = V_{Sat}$ for $v_I > v_T$.

This circuit is the threshold detector. For $V_T = 0$ the circuit becomes a zero-crossing detector.

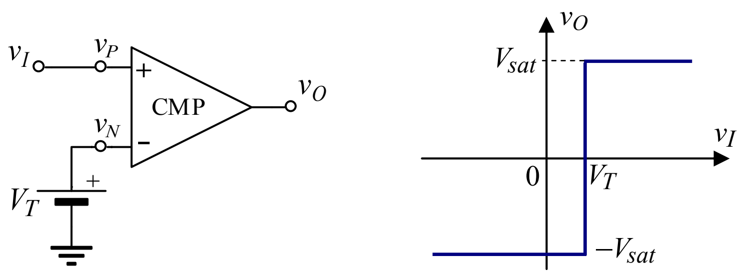

Figure – *The threshold detector*

When it is used as a comparator the op-amp has no control over v_N due to the absence of the feedback; op-amp operates in open-loop mode (and it spends most of the time in saturation). **v_N no longer track v_P!**

For a 741 op-amp the response time is an intolerable long time in many applications:

$$t_R = \frac{V_{Sat}}{SR} = \frac{13}{0.5}\mu s = 26\mu s\,.$$

The 301 op-amp (the 741 version without internal compensation slews more rapidly than the 741 op-amp.

Op-amp are intended for negative-feedback operation so they are not optimized for open-loop operation and their output saturation level are not precise nor compatible with digital circuits.

General Purpose Comparators

One of the most popular voltage comparators is LM311 presented in the next figure.

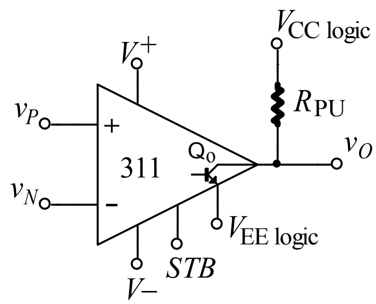

Figure – *The LM311 comparator*

The general operation of the LM311 comparator is based on the following logic:

- If $v_P < v_N$ the output transistor saturates and $v_O = V_{EE}$ (internal ground).
- If $v_P > v_N$ the output transistor is cut-off and the output assumes a so called open-collector condition. Thus, a pull-up resistor connected to a positive voltage (V_{CC}) is required to establish the output state and $v_O = V_{CC} - R_{PU}\, i_O = V_{CC}$ (in open-circuit condition – with no load resistance).
- If the strobe pin is left open (or connected to a positive voltage), the comparator function normally (as indicated previously); if the strobe pin is connected through a resistor to ground, the output assumes the open collector state irrespective of the input.

The output transistor Q_O can draw up to 50 mA.

Comparators suffer from dc input errors whose effect is to shift the output by an error:

$$E_I = V_{OS} + R_n I_N - R_p I_P$$

where V_{OS} is the offset voltage and I_N and I_P are the bias currents of the inverting and non-inverting input, respectively. Typical values for LM311 are:

- the offset voltage: V_{OS} = 2 mV,
- the bias current: $I_B = (I_P + I_N) / 2$ = 100 nA and
- the offset current is: $I_{OS} = |I_P - I_N|$ = 6 nA.

Another popular comparator is LM339 with 4 comparators in one case. All comparators share the same power supply pins (a positive one and a ground) and the comparators does not have any strobe pin. The power supply can be from 2 V to 36 V and the open-collector output can sink a typical current of 16 mA.

Comparator Applications

Level Detectors

This kind of circuits monitor a voltage and signals whenever the voltage rises above or drops below a prescribed value. The detector output is used to undertake a specific action: activate of a warning detector (such as a LED or a buzzer), turning on a motor or heather or generating of an interrupt to a microcontroller. The basic components of the circuit can be seen in the following figure:

- a voltage reference V_{REF} that establish a stable threshold,
- a voltage divider, R_1 and R_2, that scale the input and
- a comparator.

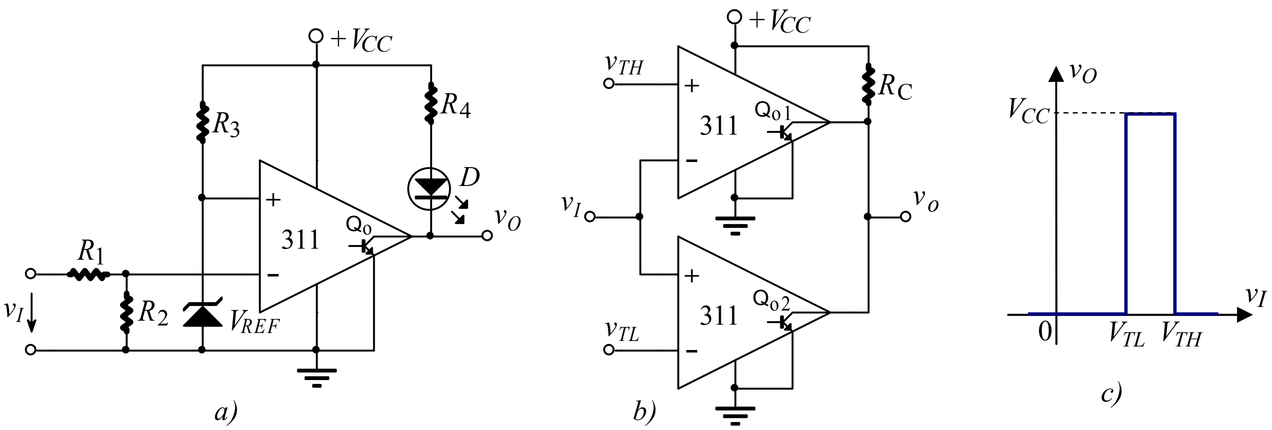

Figure – *a) Level detector; Window detector: b) the circuit and c) its VTC*

The additional resistor R_3 biases the reference diode and R_4 sets the LED current.
The threshold voltage of the input V_T, can be computed when $v_P = v_N$:

$$V_{REF} = \frac{R_1}{R_1 + R_2} v_I \Rightarrow V_T = \left(1 + \frac{R_2}{R_1}\right) V_{REF}$$

For $v_I < V_T$ the output transistor is in the OFF state (cut-off) and so is the LED.
For $v_I > V_T$ the output transistor is ON (saturated) and the LED glows.
Interchanging the input pins make the LED glow whenever v_I drops below V_T.
By combining two such circuits a window detector can be realized; an example is presented in the previous figure.

Pulse-Width Modulation

If a voltage comparator compares a slowly varying signal v_I against a high frequency wave of the triangular or saw-tooth type (v_{TR}), the outcome is a square wave with the same frequency as the triangular wave, but with its symmetry controlled by v_I in a linear fashion. The circuit and the waveforms are presented in the next figure.

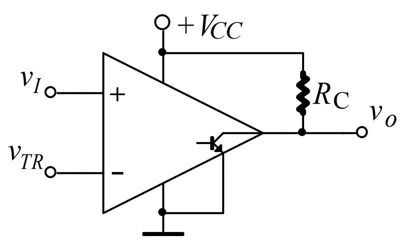

Figure – *PWM circuit (and waveforms)*

The degree of symmetry of v_O is expressed via the "duty cycle":

$$D(\%) = 100 \frac{T_H}{T_L + T_H},$$

where T_H and T_L denote, respectively the times spend by the output voltage v_O in the "High" and "Low" state within a given cycle of v_{TR}. The sum of these two times is the period of the triangular wave. If v_I varies between 0 and V_M, D varies over 0 to 100%.
Pulse width modulation (PWM) finds applications in signal transmission and power control.

Schmitt Triggers – Amplifiers with Positive Feedback

While the negative feedback tends to keep the amplifier in the linear region, the positive feedback forces it into saturation, in one of the two stable states at the output: V_{OH} or V_{OL}.

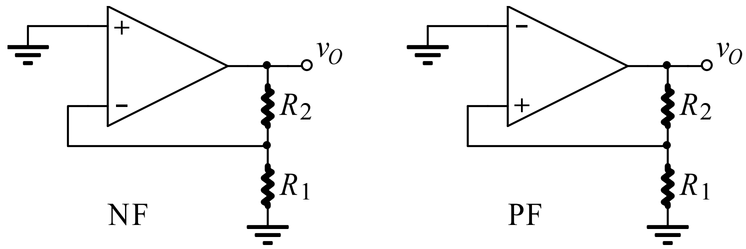

Figure – *The negative feedback (applied to the inverting input) compared to the positive feedback (applied to the non-inverting input) – The input is not represented (the input source connected to ground will replace one of the ground connection points)*

Inverting Schmitt Trigger

The circuit presented in the next figure is an inverting type threshold detector.

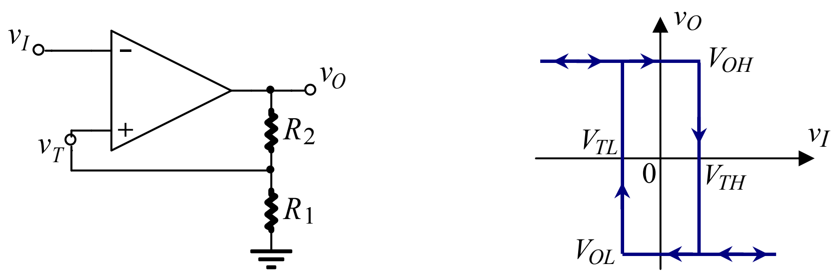

Figure – *Inverting Schmitt trigger and its VTC*

The threshold voltage of the comparator is controlled by the output:

$$v_T = \frac{R_1}{R_1 + R_2} v_O .$$

Since the output has two stable states (V_{OH} and V_{OL}), this threshold has two possible values, the high threshold V_{TH} and the low threshold V_{TL}:

$$V_{TH} = \frac{R_1}{R_1 + R_2} V_{OH} \text{ and } V_{TL} = \frac{R_1}{R_1 + R_2} V_{OL} .$$

The best way to visualize the circuit behavior is by deriving its VTC:

- If $v_I << 0$ ($v_I < V_{TL}$), $v_O = V_{OH}$ and $v_P = V_{TH}$;
- As v_I increases to $v_I = V_{TH}$, the output switches to $v_O = V_{OL}$ and $v_P = V_{TL}$;
- As v_I decreases to $v_I = V_{TL}$, the output switches back to $v_O = V_{OH}$ and $v_P = V_{TH}$.

v_P snoops away from v_N; this behavior is opposite to that of negative feedback that keeps $v_P = v_N$.

The hysteresis width is:

$$\Delta V_T = V_{TH} - V_{TL} = \frac{R_1}{R_1 + R_2}\left(V_{OH} - V_{OL}\right).$$

It depends on the ratio R_1/R_2. For R_1/R_2=0, the circuit becomes a “zero crossing detector”.

Non-Inverting Schmitt Trigger

The circuit in the next figure is similar the inverting trigger except that v_I is now applied to the non-inverting side.

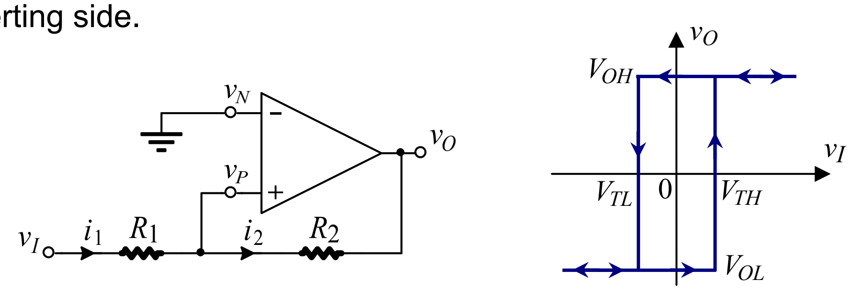

Figure – *Non-inverting Schmitt trigger and its VTC*

For $v_I << 0$, the output will saturate at $v_O = V_{OL}$. If we want v_O to switch state, v_I should be high enough to bring v_P to cross $v_N = 0$ (since this is when the comparator trips). In this point $v_P = v_N = 0$ and $v_I = V_{TH}$. Same current flows in both resistors $i_1 = i_2$, that is:

$$\frac{V_{TH} - 0}{R_1} = \frac{0 - V_{OL}}{R_2} \text{ and } V_{TH} = -\frac{R_1}{R_2} V_{OL}.$$

Once v_O has snapped to V_{OH}, v_I must be lowered if we want v_O to snap back to V_{OL}:

$$\frac{V_{OH} - 0}{R_2} = \frac{0 - V_{TL}}{R_1} \text{ and } V_{TL} = -\frac{R_1}{R_2} V_{OH}.$$

The hysteresis is:

$$\Delta V_T = V_{TH} - V_{TL} = \frac{R_1}{R_2}\left(V_{OH} - V_{OL}\right).$$

and it can be varied by changing the resistors ratio R_1/R_2. For $R_1/R_2=0$ we obtain a non-inverting zero-crossing detector.