

PLECS

*DEMO MODEL*

## Operational Amplifier Circuits

Last updated in PLECS 4.3.1

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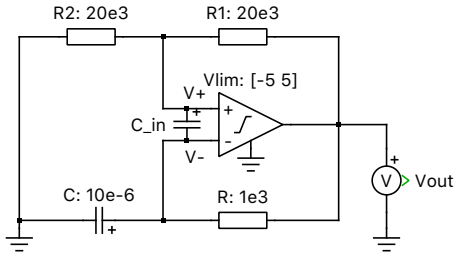
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# 1 Overview

This demonstration shows several op-amp circuits, including a multivibrator, integrator and differentiator.

## 2 Model

### 2.1 Multivibrator with comparator



**Figure 1: Multivibrator**

The multivibrator amplifier is an astable oscillator which generates rectangular waveforms at the output using an RC network at the inverting input and a voltage divider at the non-inverting input of the amplifier.

This configuration switches between its two unstable states, with the time spent in each state controlled by the charging or discharging of the capacitor through a resistor.

Initially, the capacitor starts charging up to  $V_{out}$ . Once the voltage at the inverting terminal becomes equal to or greater than the voltage at the non-inverting terminal,  $\lambda V_{out}$ , the op-amp output clamps to the negative supply rail, thus causing the capacitor charge go to zero and start charging to the new value of  $V_{out}$ . This goes on until the negative supply rail reaches the  $-\lambda V_{out}$  threshold, and the output changes state again, reinitiating the cycle. This produces a steady, continuous square wave pulse train at the output.

The RC time constant determines the rate of capacitor charge/discharge, or the period of the output waveform, and the voltage divider network sets the reference voltage level,  $\lambda V_{out}$ .

A small capacitance  $C_{in}$  is required for decoupling of negative feedback.

#### Formula derivation

From voltage divider,

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

General charging equation for a capacitor with an original charge:

$$q = CV \cdot (1 - e^{-\frac{t}{RC}}) + q_0 \cdot e^{-\frac{t}{RC}}$$

For  $V = V_{out}$  and  $q_0 = \lambda CV_{out}$ ,

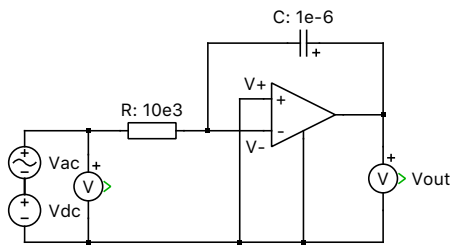
$$q = -CV_{out} \cdot (1 - e^{-\frac{t}{RC}}) + \lambda CV_{out} \cdot e^{-\frac{t}{RC}}$$

$$T = 2RC \cdot \ln \left( \frac{1 + \lambda}{1 - \lambda} \right)$$

This result is also obtained for the discharging period of the operation, assuming the magnitudes of the rails are equal, meaning  $t_{\text{charge}} = t_{\text{discharge}}$ .

Multivibrators are used in a variety of applications where square waves or timed intervals are required, such as a flashing light.

## 2.2 Inverting integrator



**Figure 2: Inverting integrator**

An integrator produces an output voltage, which is proportional to the integral of the input voltage.

$$V_{\text{out}} = -\frac{1}{RC} \cdot \int_0^t v_{\text{in}} dt$$

### Formula derivation

Because of virtual ground and infinite impedance of the input terminals of the op-amp, all of the input current flows through R and C:

$$i_{\text{in}} = \frac{v_{\text{in}} - V_-}{R} = \frac{v_{\text{in}}}{R} = i_R = i_C$$

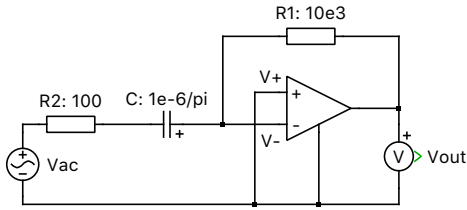
$$v_C = V_- - V_{\text{out}} = -V_{\text{out}}$$

$$i_C = C \cdot \frac{dv_C}{dt} = -C \cdot \frac{dV_{\text{out}}}{dt} = \frac{v_{\text{in}}}{R}$$

$$\frac{dV_{\text{out}}}{dt} = -\frac{1}{RC} \cdot v_{\text{in}}$$

$$V_{\text{out}} = -\frac{1}{RC} \cdot \int_0^t v_{\text{in}} dt$$

An application for this circuit could be integrating water flow and measuring the total quantity of water that has passed by the flowmeter.



**Figure 3: Inverting differentiator**

## 2.3 Inverting differentiator

The differentiator op-amp configuration produces an output voltage that is proportional to the rate of change of the input voltage by measuring the current through a capacitor:

$$V_{\text{out}} = -RC \cdot \frac{dv_{\text{in}}}{dt}$$

The right-hand side of the capacitor is held at 0 volts due to the virtual ground effect. Therefore, current through the capacitor is solely due to change in the input voltage. A steady input voltage will not cause a current through C, but a changing input voltage will. The faster the voltage changes, the larger the magnitude of the output voltage.

### Formula derivation

Because of virtual ground and the infinite impedance of an op-amp, all current flowing through the capacitor also flows through R1:

$$i_C = i_{R_1} = \frac{V_- - V_{\text{out}}}{R_1} = \frac{-V_{\text{out}}}{R_1}$$

$$v_C = v_{AC} - i_C R_2 \approx v_{AC}$$

(the very small resistance R2 is needed for convergence purposes)

$$i_C = C \cdot \frac{dv_C}{dt} = C \cdot \frac{dv_{AC}}{dt} = -\frac{V_{\text{out}}}{R_1}$$

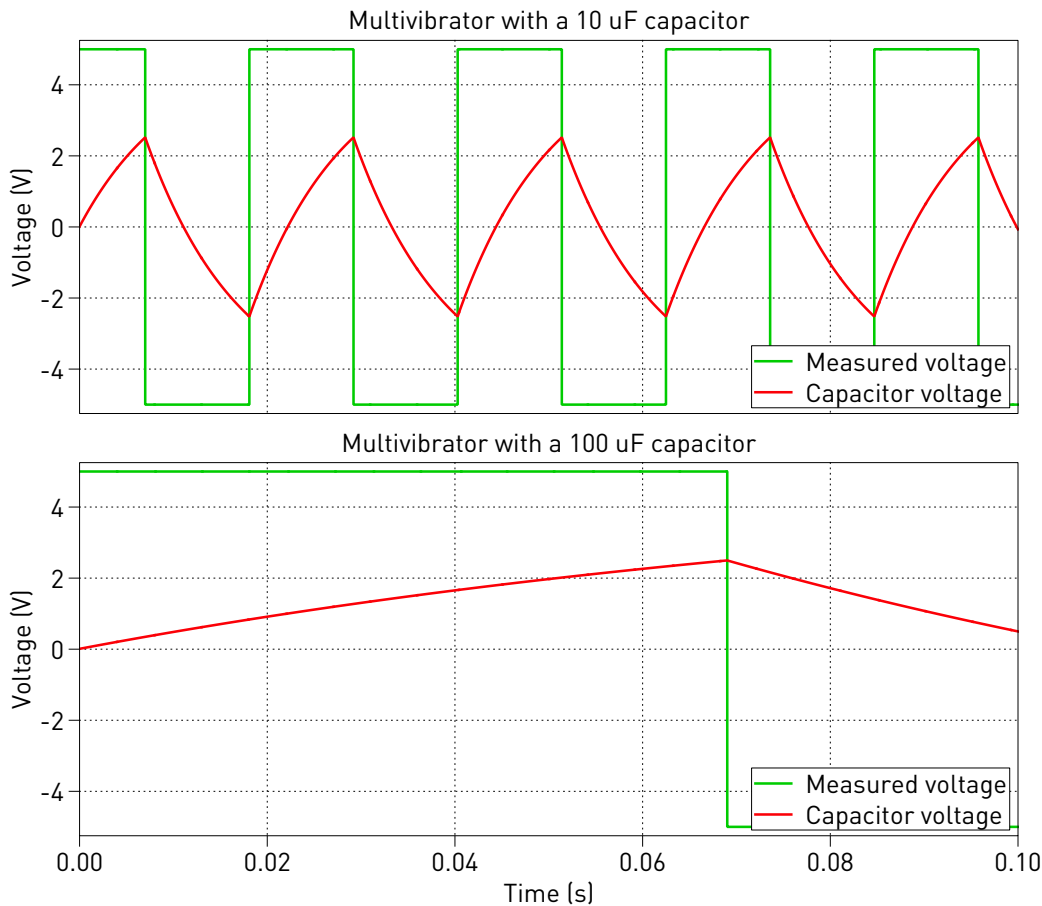
$$V_{\text{out}} = -R_1 C \cdot \frac{dv_{AC}}{dt}$$

An application for this circuit could be monitoring the rate of change of temperature in an environment where too high or too low of a temperature rise is detrimental and would, thus, trigger an alarm or a notification using additional circuitry on the output.

## 3 Simulation

### 3.1 Multivibrator with comparator

Increase the capacitance value to 100  $\mu\text{F}$  and observe the increase in the amount of time it takes to charge up the capacitor, as shown in Fig. 4. Increase the left-most resistor to 25 k $\Omega$  and observe the change in the output voltage switching frequency.



**Figure 4: Multivibrator circuit simulations comparison**

### 3.2 Inverting integrator

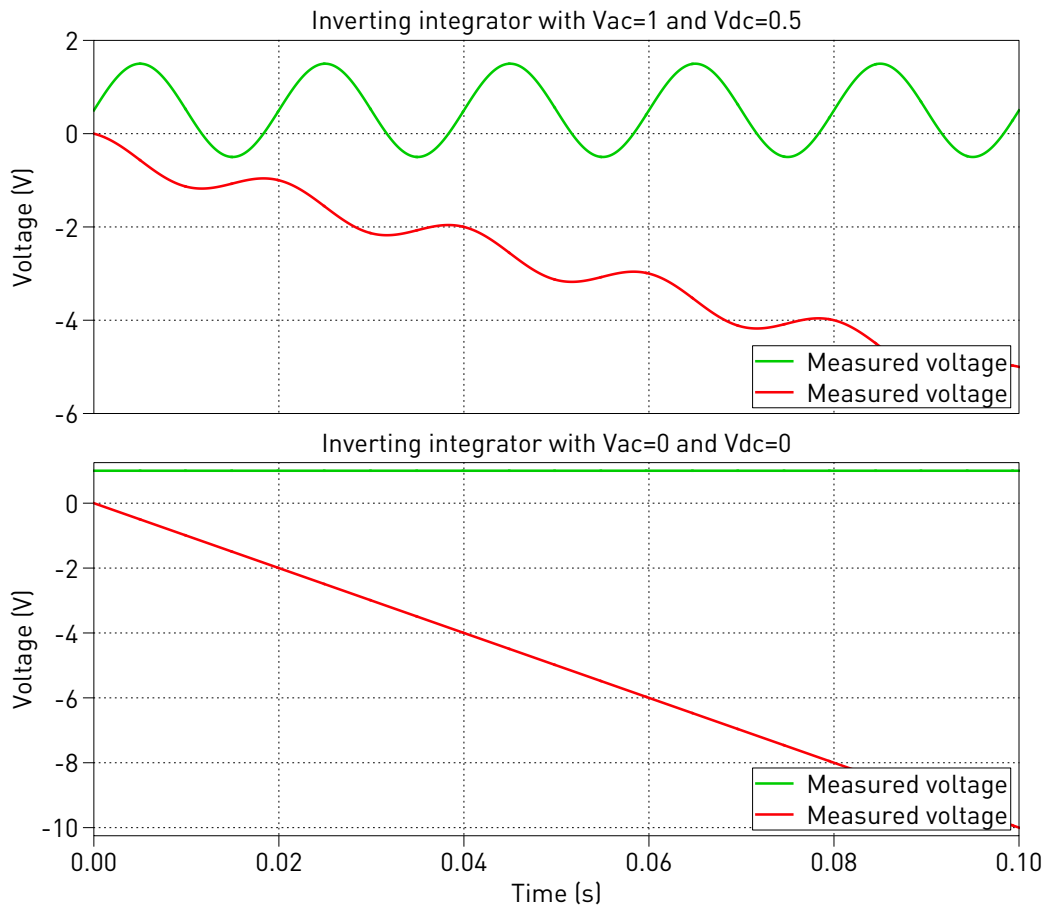
Set the amplitude and frequency of the AC voltage source to 0 and the DC voltage source to 1 V. The output should look like the one in Fig. 5. If a fixed voltage is applied to the input of an integrator, the output voltage will be a ramp with a constant slope of the negative input voltage multiplied by a factor of  $1/RC$ .

### 3.3 Inverting differentiator

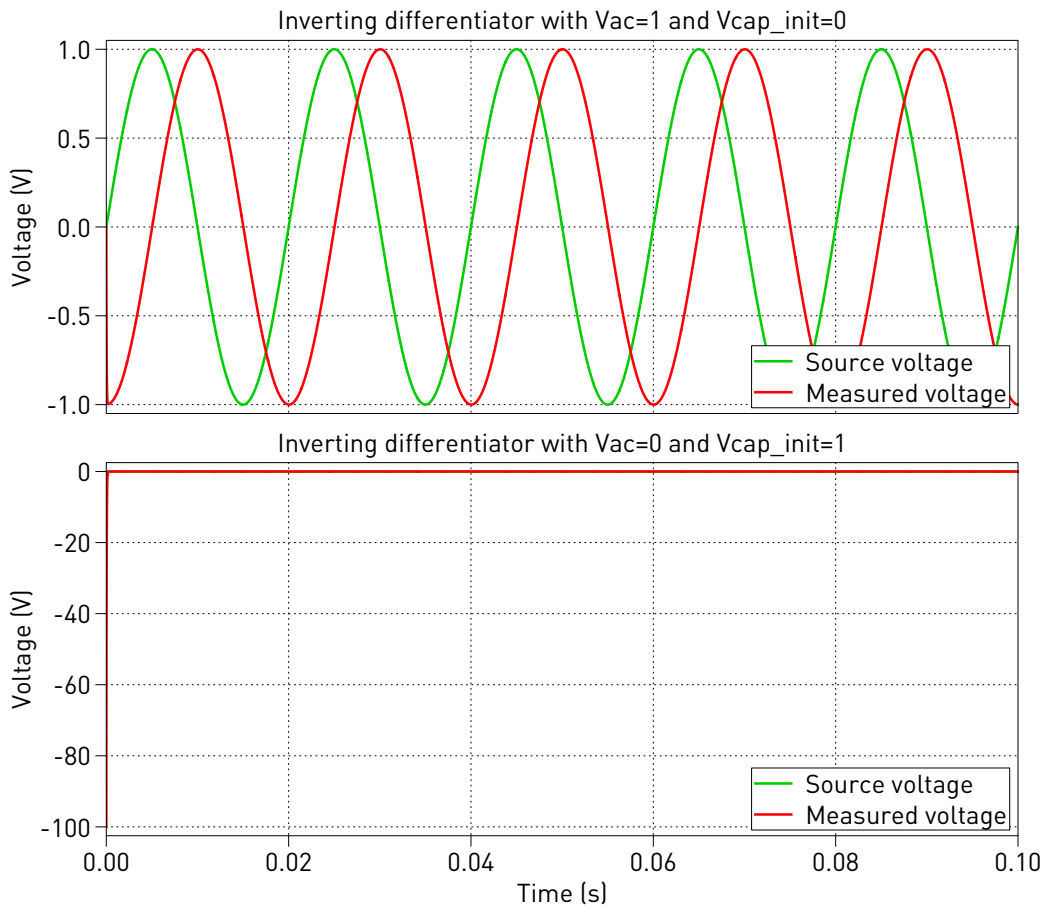
Set the amplitude and frequency of the AC voltage source to 0 and the initial capacitor voltage to 1 V. Observe the output after there is no change in the input voltage, as shown in Fig. 6. After the capacitor  $C$  discharges, do you see what you expected? If the input voltage is constant,  $dv/dt$  is zero and the output voltage is zero.

## 4 Conclusion

Operational amplifiers are a core part of analog electronics and can perform many different operations depending on the passive component configurations around them. For more op-amp examples, visit the Analog Electronics Academy page on Plexim's website.



**Figure 5: Inverting integrator circuit simulations comparison**



**Figure 6: Inverting differentiator circuit simulations comparison**

## Revision History:

PLECS 4.3.1      First release

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