Abstract—This document explains the three circuit sections that constitute the Pulse-Width Modulation (PWM) circuit: a Schmitt trigger, an integrator, and a comparator.

I. PWM Circuit Overview

Fig. 1 shows the schematic (sans power supply connections) for the Pulse-Width Modulated (PWM) circuit of Lab 4. Boxes are drawn around the three circuit sections that constitute the PWM circuit: a Schmitt trigger, an integrator, and a comparator. The first two circuit sections work in tandem to produce a triangle waveform, while the third circuit section compares the triangle waveform with a reference voltage to produce a PWM waveform. Fig. 2 shows the waveforms at the output of each section superimposed over time.

The remainder of this document touches upon the operation of each circuit section in turn.
II. **INTEGRATOR**

Figure 3. Integrator waveforms.

The output of the Schmitt trigger, $v_1$, is always either high or low. The current in $R_3$ is constant and positive or constant and negative. When the current is positive, it fills $C$ with charge. When the current is negative, it drains $C$ of charge. The $C$ acts like a tank being filled and emptied. The left side of the $C$ stays at zero volts. The op-amp adjusts $v_2$ so as to make the left side of $C$ stay at zero volts. If we think of $C$ as a tank storing charge, it is as though the top of the water stays at ground level, and the bottom of the tank moves up or down as water goes into or out of the tank.

When $v_1 = -V_{rail}$, we have the following current flowing toward the minus input of the second op-amp and through the capacitor:

$$I = \frac{V_{rail}}{R_3} = C \frac{\Delta V_C}{\Delta t}$$  \hspace{1cm} (1)

We solve for the slope of $v_2$, which is the slope of the voltage on the capacitor, since $v_- = 0V$.

$$v_2 \text{ slope} = \frac{\Delta V_C}{\Delta t} = \frac{V_{rail}}{R_3 C} \approx \frac{5V}{10k \cdot 0.022 \mu s} = \frac{5V}{0.22 \text{ ms}} \approx 22.7 \text{ V/ms}$$  \hspace{1cm} (2)

To find the peak value of $v_2$ we analyze the Schmitt trigger.
III. **Schmitt Trigger**

![Figure 4. Schmitt trigger waveforms.](image)

The voltage at the $v_+$ input of the Schmitt trigger is found by using a voltage divider driven on two sides, by $v_1$ and $v_2$. Note how the resistor values enter into the calculation.

$$v_+ = \frac{13k\Omega \cdot v_{2pk} - 10k\Omega \cdot V_{rail}}{13k\Omega + 10k\Omega} = \frac{13v_{2pk} - 50V}{23}$$  \hspace{1cm} (2)

The Schmitt trigger output changes when the value $v_-$ crosses $v_+ = 0$ V. Using this idea allows us to calculate the value of $v_2$ when the output of the Schmitt trigger changes.

$$v_2 = 0\text{ V} \Rightarrow v_{2pk} = \frac{50\text{ V}}{13} = 3.85\text{ V}$$  \hspace{1cm} (2)

We use the slope of $v_2$ to calculate the time at which the peak value of $v_2$, (which occurs when $v_1$ switches), will occur.

$$t_{pk} = \frac{3.85\text{ V} - 3.85\text{ V}}{22.7\text{ V/ms}} \approx 0.34\text{ ms}$$  \hspace{1cm} (2)

When $v_1$ switches, the value at $v_+$ of the first op-amp jumps to a new value. We use the voltage divider formula again to calculate that value.

$$v_+ = \frac{13k\Omega(3.85\text{ V}) + 10k\Omega(5\text{ V})}{23k\Omega} \approx 4.35\text{ V}$$  \hspace{1cm} (2)
IV. Comparator

The comparator output is high when $v_2$ is higher than the $v_-$ input voltage of the last op-amp. The value of $v_-$ is set by potentiometer $R_4$. Note that the potentiometer creates a voltage divider. Adjusting $R_4$ changes the voltage at the $v_-$ input. In Fig. 5, the voltage is shown as 1 V. The higher the value of $v_-$, the shorter the time $v_3$ stays high.