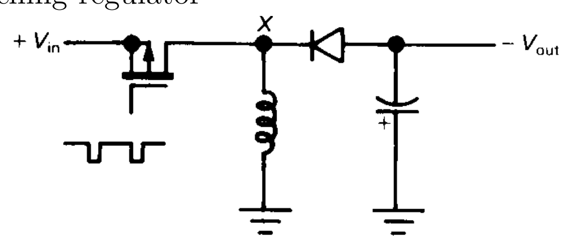
1. **Switching regulator**

   (a) **Draw a inverting switching regulator**

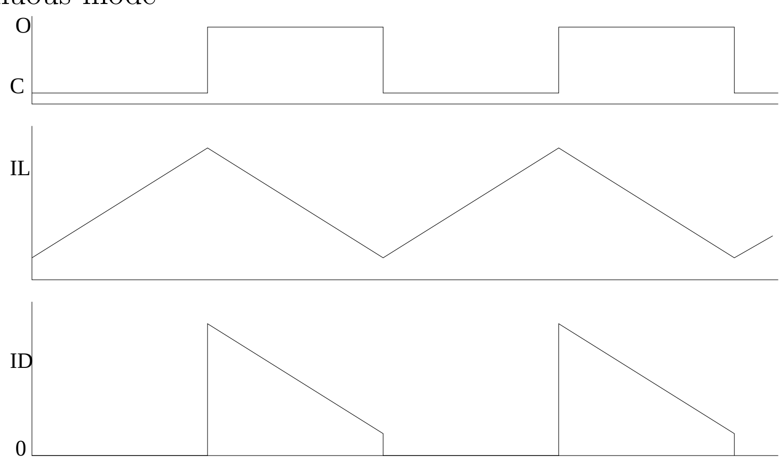
   (b) **Carefully sketch the switch state, the current through the diode and the current through the inductor for continuous mode using any voltage ratio you like (you don't need to specify the voltage ratio).**

   (c) **Same, but for discontinuous mode, using the same voltage ratio as in the previous question.**

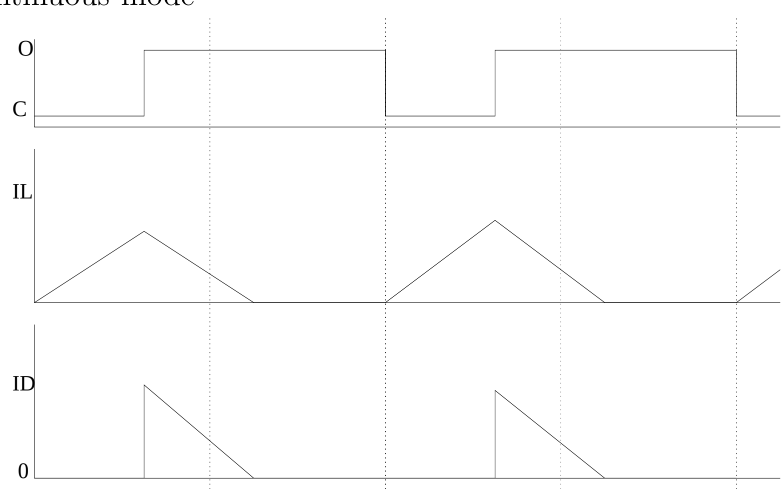
(a) Inverting switching regulator



(b) Continuous mode



(c) Discontinuous mode



2. **Linear regulator**

(a) **Design a 5 volt regulator with outboard power transistor using the 723.**

(b) **Add a current sense resistor to limit the current to 1 A.**

(c) **Add a foldback circuit to make the short-circuit current 0.5 A. (For speed, you may assume the current sense resistor does not change from the previous question, if you like)**

(a) Divide the supplied reference voltage 7.15 V according to a voltage divider $R_2/\left(R_1+R_2\right)$,

$$\frac{R_2}{R_1+R_2}=\frac{5}{7.15}$$

$$R_2=0.7R_1+0.7R_2$$

$$0.7R_1=0.3R_2$$

$$R_2=0.43\,R_1$$

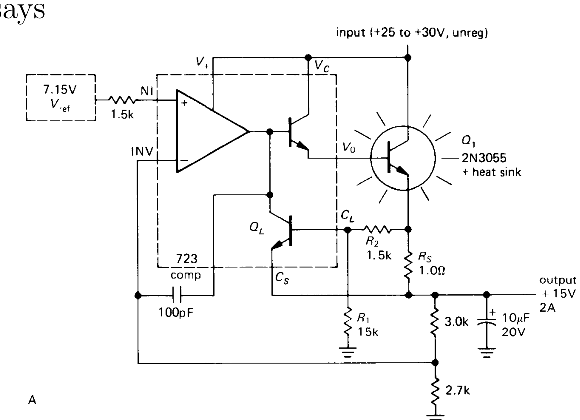
Choose $R_1=1\,\mathrm{k}\Omega$, and $R_2=430\,\Omega$.

(b) We want the BJT to activate when $V_{BE}=0.5\,\mathrm{A}$, so

$$I_{\max}R_S=V_{BE,on}$$

$$R_S=\frac{V_{BE,on}}{I_{\max}}=\frac{0.5}{1}=0.5\,\Omega$$

(c) Let's assume that R_S stays the same. In that case we use the formula from the book which says



$$\frac{I_{\max}}{I_{\mathrm{SC}}}=1+\left(\frac{R_2}{R_1+R_2}\right)\frac{V_{\mathrm{reg}}}{V_{BE,on}}$$

$$\frac{R_2}{R_1+R_2} = \left(\frac{I_{\max}}{I_{SC}} - 1\right)\frac{V_{BE,on}}{V_{\text{reg}}} = \left(\frac{1}{0.5} - 1\right)\frac{0.5}{5} = 0.1$$

$$R_2 = 0.1R_1 + 0.1R_2$$

$$0.9R_2 = 0.1R_1$$

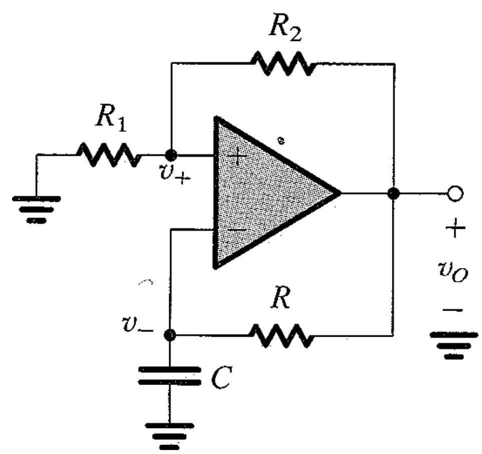
$$R_2 = 0.11R_1$$

Choose $R_1 = 2\,\text{k}\Omega$, and $R_2 = 220\,\Omega$.

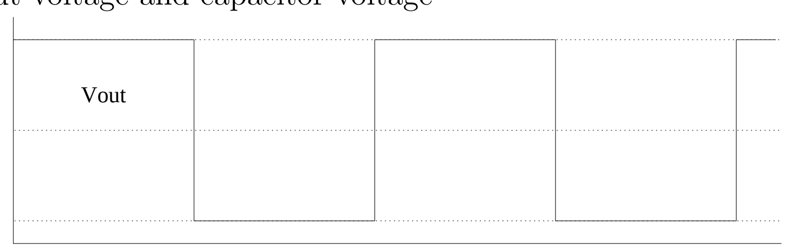
3. Consider the following astable circuit, in which $C = 100\,\text{nF}$, and $R = 10\,\text{k}\Omega$, $R_2 = R_1$ and $L_+ = -L_-$.

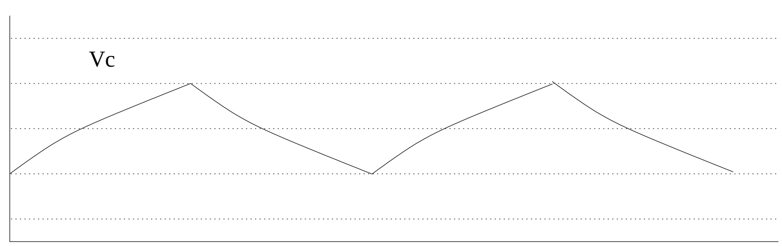
(a) Sketch the output voltage and the voltage across the capacitor as a function of time for at least two periods.

(b) Determine the period of oscillation.



(a) Output voltage and capacitor voltage





(b) The relaxation time constant is RC. We can see that it drops by 2/3 toward it's goal, so the half period is found from

$$\exp\left(-\frac{T/2}{RC}\right) = 1 - 2/3 = 1/3$$

$$T = -2RC\ln\frac{1}{3} = 2RC\ln 3 = 2\times 10\times 10^3\times 100\times 10^{-9}\times\ln 3 = 2.2\,\mathrm{ms}$$

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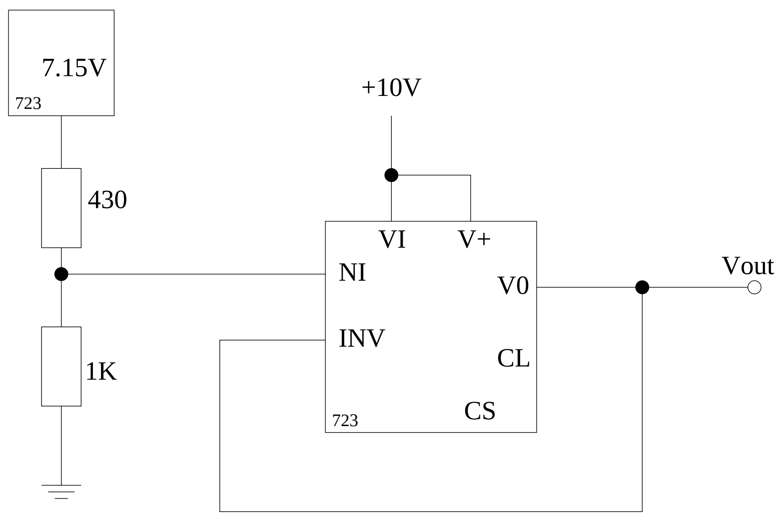
1. **Linear regulator**

(a) **Use a 723 to make a $5\,$V regulated supply from a $10\,$V unregulated input.**

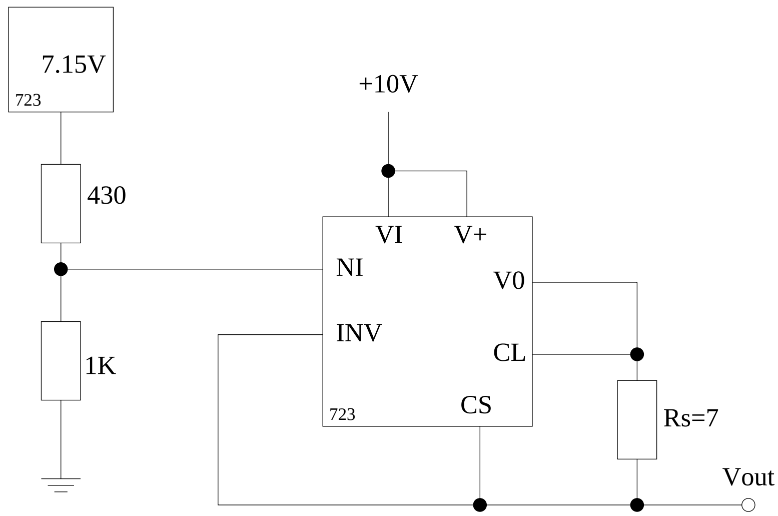


(b) **Add current limiting of $100\,$mA.**

The current limiting resistor goes between CL and CS, and we take the output from CS. The size of the current limiting resistor is defined by

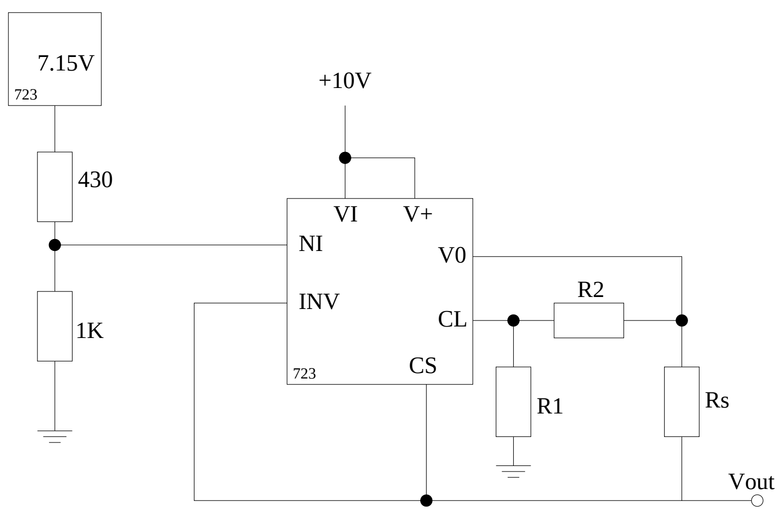
$$V_D = R_S I_{\max}$$

For $I_{\max} = 100\,\mathrm{mA}$ and $V_D = 0.7\,\mathrm{V}$, we get $R_S = 7\,\Omega$. The modified circuit now looks like



(c) **Modify to include foldback current limiting to 30 mA when the output is shorted.**

Now the circuit looks similar to Horowitz & Hill Figure 6.7, with a different values for the current sensing resistor, and two additional resistor R_1 and R_2.



The equations we need are also listed in Figure 6.7,

$$\frac{I_{\text{max}}}{I_{\text{SC}}} = 1 + \frac{R_2}{R_1 + R_2}\frac{V_{\text{reg}}}{V_{\text{BE}}}$$

We get

$$\frac{R_2}{R_1 + R_2} = \left(\frac{I_{\text{max}}}{I_{\text{SC}}} - 1\right)\frac{V_{\text{BE}}}{V_{\text{reg}}} = \left(\frac{100}{30} - 1\right)\frac{0.7}{5} = 0.33$$

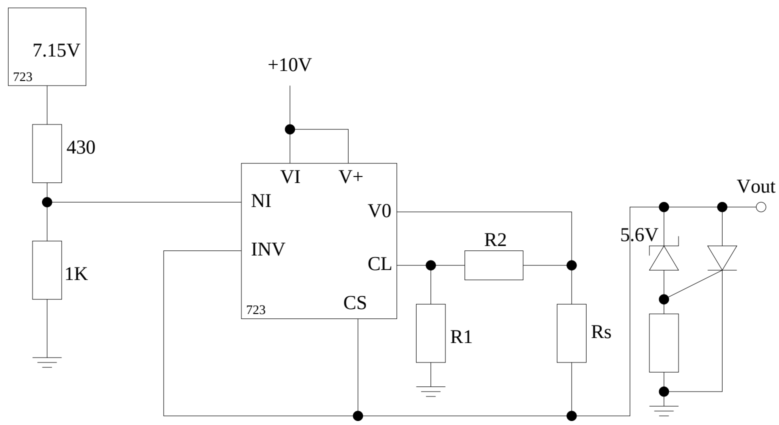
or $\frac{R_1}{R_2} = 2$. So let us choose $R_1 = 10\,\text{k}\Omega$ and $R_2 = 5\,\text{k}\Omega$. Next we want to find the size of the current-sensing resistor,

$$I_{\text{SC}} = \frac{1}{R_S}\frac{R_1 + R_2}{R_1}V_{\text{BE}}$$

or

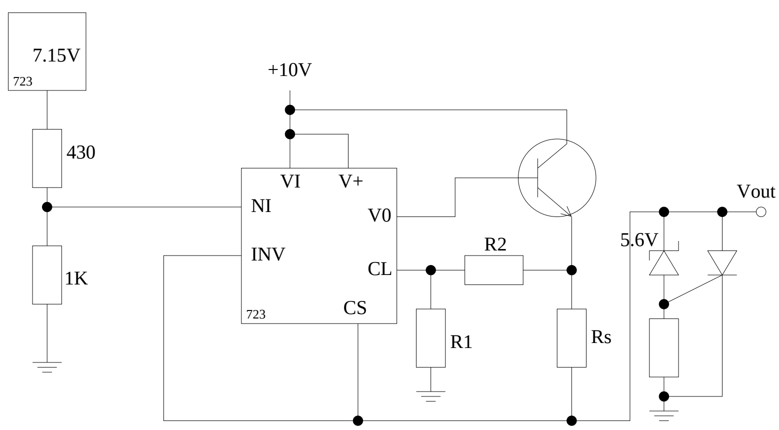
$$R_S = \frac{1}{I_{\text{SC}}}\frac{R_1 + R_2}{R_2}V_{\text{BE}} = \frac{1}{30\times 10^{-3}}\frac{10+5}{5}0.7 = 70\,\Omega$$

(d) **Add a overvoltage crowbar which activates at $6.2\,$V. Use an SCR and a Zener diode.**



The SCR turns on at roughly $0.6\,$V, so we use a $5.6\,$V Zener diode, and a small resistor (around $100\,\Omega$).

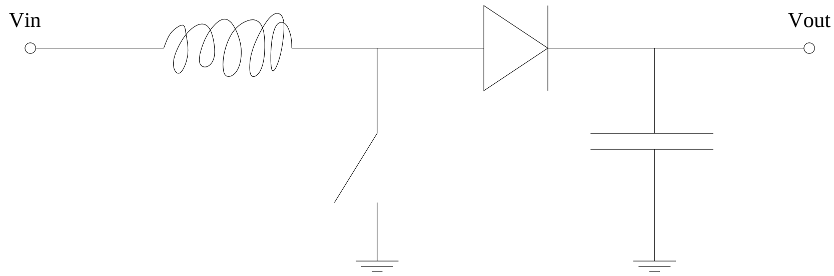
(e) **Modify the circuit to use an external power transistor while raising the current limit to $1\,$A and foldback current to $300\,$mA.**



Since the ratio of maximum to short-circuit current is the same, we can keep the same values of $R_1 = 10\,\text{k}\Omega$ and $R_2 = 5\,\text{k}\Omega$. Since the short-circuit current is now ten times as large, the new value for the current-sensing resitor should be ten times as small, $R_2 = 7\,\Omega$.

2. Switching regulator

(a) **Draw a step-up switching regulator.**

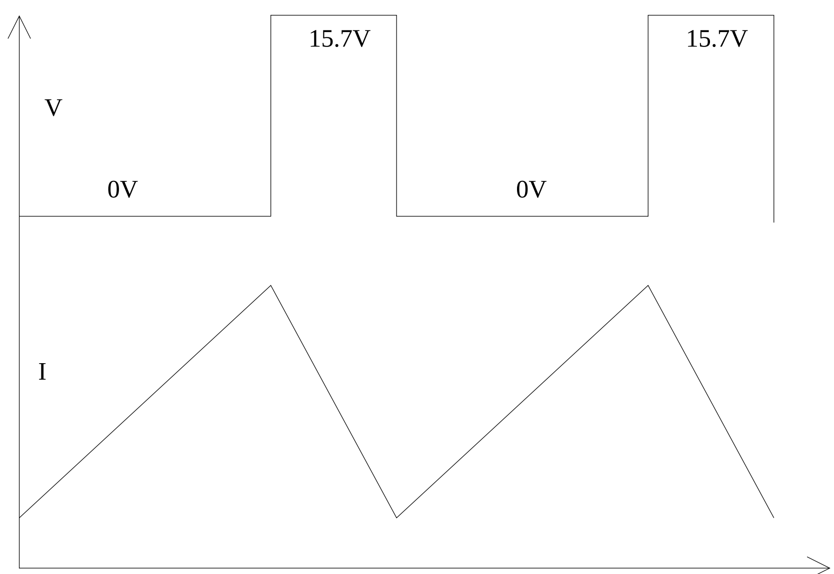


(b) **Draw the voltage at the inductor/diode node, and the inductor current, when input is $5\,\mathrm{V}$, the output is $15\,\mathrm{V}$, and the regulator is operating in continuous mode.**

The important expression here is

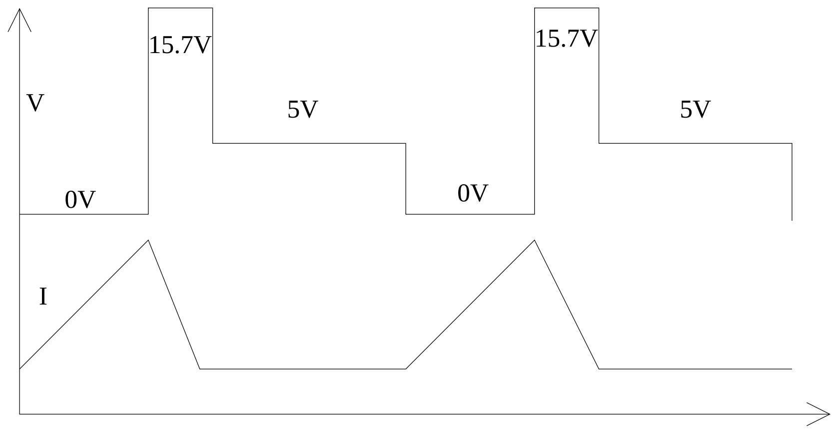
$$V = L\frac{dI}{dt}$$

When the switch is closed, the voltage across the inductor is $5\,\mathrm{V}$. When the switch is open, the voltage across the inductor is $-10\,\mathrm{V}$ So the inductor discharges twice as fast as it charges. Therefore the charging cycle should be approximately twice as long as the discharging cycle.

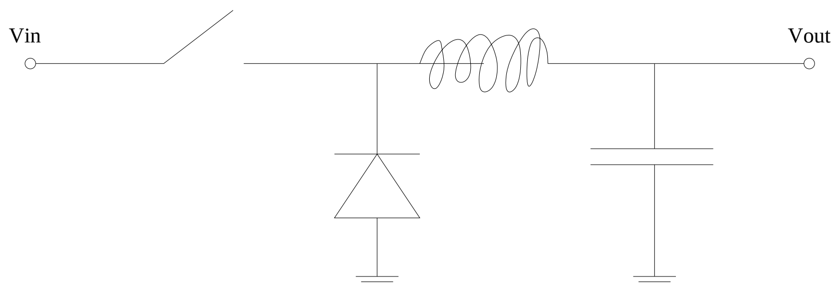


(c) **Same, but for discontinuous mode operation.**

In discontinuous mode the inductor is completely discharged for part of the cycle when the switch is open. What that means is that first of all, the charge cycle is shorter than during discontinuous mode (because the slopes of the currents are still the same), and the voltage at the inductor/diode node is $5\,\mathrm{V}$.



(d) **Draw a step-down switching regulator.**

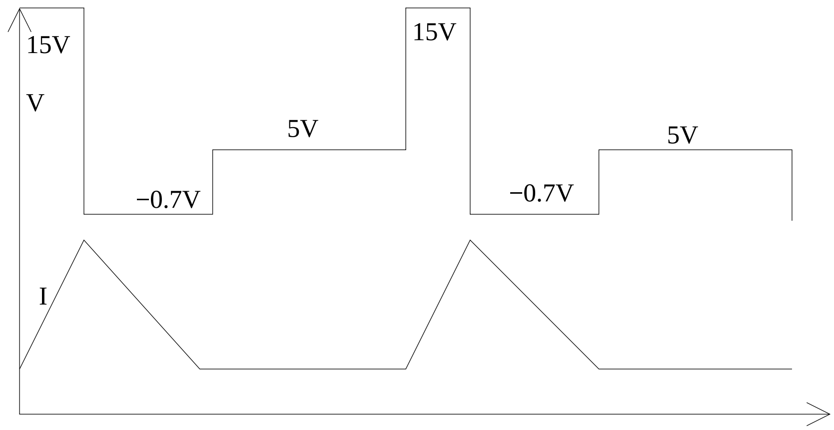


(e) **Draw the voltage at the inductor/diode node when the input voltage is $15\,\mathrm{V}$ and the output is $5\,\mathrm{V}$, for discontinuous operation.**

We again turn to the equation

$$V = L\frac{dI}{dt}$$

When the switch is closed, the voltage across the inductor is approximately $10\,\mathrm{V}$. When the switch is open, the voltage across the inductor is approximately $5\,\mathrm{V}$ (ignoring the voltage drop across the diode). Thus the inductor charges twice as fast as it discharges. When the inductor is charging, the node is at the input voltage, $15\,\mathrm{V}$. When the inductor is discharging, the node is at $-0.7\,\mathrm{V}$. Whent he inductor is completely discharge, the node is at the same voltage as the output, $5\,\mathrm{V}$.



(f) **Specify a design that will allow the step-down to operate in continuous mode to a current of 10 mA.**

We use the equation

$$I_{\text{min}} = \frac{V_{\text{out}}}{2L} f^{-1} \left(1 + \frac{V_{\text{out}}}{V_{\text{in}}}\right)^{-2}$$

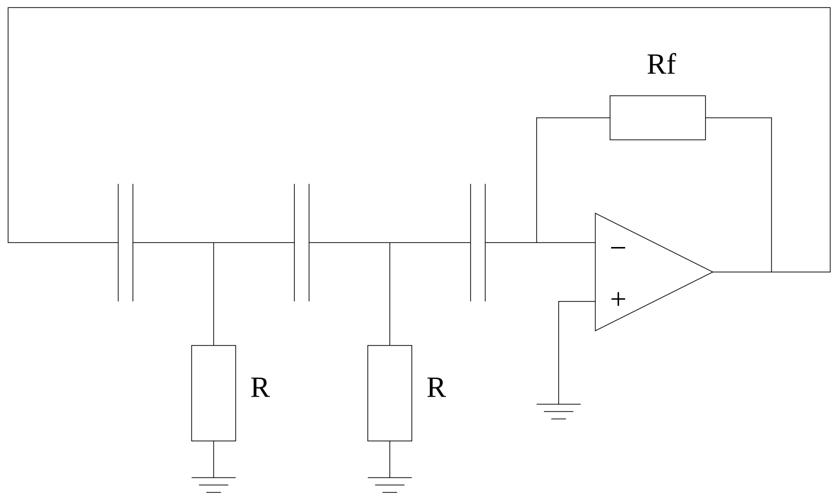
We pick values for L and f to make $I_{\text{min}} = 10\,\text{mA}$. I will arbitrarily pick $L = 10\,\text{mH}$, and the figure out what f should be.

$$\begin{aligned} f =& \frac{V_{\text{out}}}{2L} \frac{1}{I_{\text{min}}} \left(1 + \frac{V_{\text{out}}}{V_{\text{in}}}\right)^{-2} \\ =& \frac{5}{2 \times 10 \times 10^{-3}} \frac{1}{10 \times 10^{-3}} \left(1 + \frac{5}{15}\right)^{-2} \\ =& 14\,\text{kHz} \end{aligned}$$

3. **Sinusoidal oscillator**

Consider the phase-shift oscillator in Sedra & Smith Figure 13.8 (page 1175). The loop transfer function is given in exercise 13.5 at the bottom of the same page.

(a) **Draw the oscillator circuit without the output limiting circuitry.**



(b) **Specify the component values which will set the oscillation frequency to $15\,\mathrm{kHz}$**

The loop transfer function is specified in the book, and is

$$L(j\omega) = \frac{\omega^2 C^2 R R_f}{4 + j\left(3\omega CR - \frac{1}{\omega CR}\right)}$$

We want the oscillation frequency $f_0 = 15\,\mathrm{kHz}$, which means we want $\omega_0 = 2\pi 15 \times 10^3\,\mathrm{s}^{-1}$. In order for that to be the oscillation frequency, the loop transfer function must have zero phase. That is the case when

$$3\omega_0 CR - \frac{1}{\omega_0 CR} = 0$$

or

$$CR = \frac{1}{\sqrt{3}\omega_0} = 6.1 \times 10^{-6}$$

If we choose $R = 1\,\mathrm{k}\Omega$, then we get $C = 6.1 \times 10^{-6}/10^3 = 6.1 \times 10^{-9} = 6.1\,\mathrm{nF}$.

(c) **Specify any remaining component values such that oscillation will be sustained.**

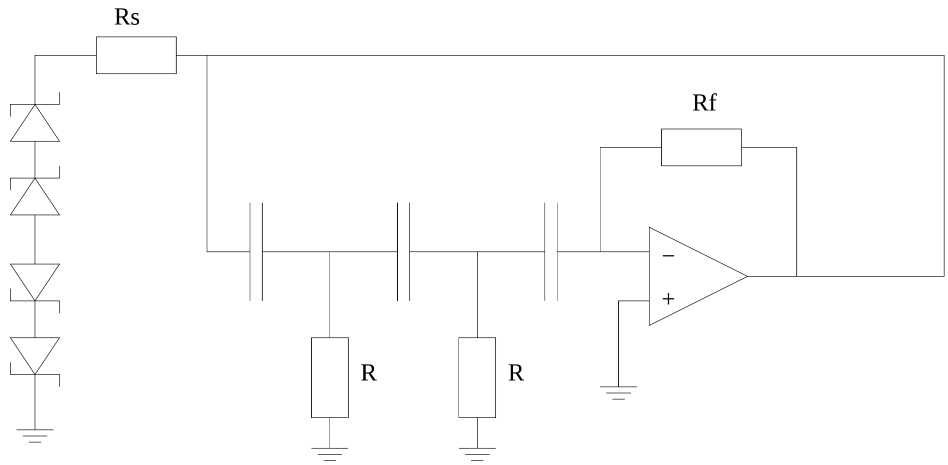
In order to sustain oscillations we also require the that amplitude of the loop gain at the oscillation frequency is at least 1. Thus

$$1 = |L(j\omega)| = \frac{1}{4}\omega_0^2 C^2 R R_f$$

or

$$R_f = \frac{4}{\omega_0^2 C^2 R} = \frac{4}{\left(2\pi 15 \times 10^3 \times 6.1 \times 10^{-9}\right)^2 1 \times 10^3} = 12\,\mathrm{k}\Omega$$

(d) **Design a approximately $\pm 12\,\mathrm{V}$ limiting circuit for this oscillator using $5.6\,\mathrm{V}$ Zener diodes. Don't forget a small resistor. Where does it go, and why?**



If we put two $5.6\,\mathrm{V}$ Zener diodes in series, the voltage drop across them will be $11.2\,\mathrm{V}$. If we add to that the forward voltage drop across two other Zener diodes, the total voltage drop will be $11.2 + 1.4 = 12.6\,\mathrm{V}$. So if we place four Zener diodes in series as shown on the figure, we have a $\pm 12.6\,\mathrm{V}$ limiting circuit.

The small resistor is included in order to limit the amount of current that the op-amp must supply.