EE 251

Basic Electrical Engineering

Application Specific Circuits

Circuits are the heart of all electronic systems. What have been discussed in the previous chapters were the basics of analyzing and later designing circuits to perform specific tasks. However, this book is not intended for electrical engineers to accomplish this task. Instead, we want to show all engineers an overview of the different applications where circuits of different classifications are used. In the coming sections, we give brief and simple conceptual designs that serve specific functions. The circuits shown are called application-specific circuits, and as said very basic and conceptual. Real world circuits are much more complicated, ensure better performance, and involve solving more detailed real problems.

The style in which we present these circuits is as follows:

- **Function**: a description of the main function of the circuit
- **Circuit**: the schematic diagram of the circuit
- **Utilization**: the possible applications where this design is used
- **Equations**: the simple design equations to modify the design specifications
- **Example**: a solved example on designing with this circuit

Oscillators

Oscillators or generators are circuits that produce signals with specific waveforms, amplitudes, and frequencies. Figure (1) shows some examples of different waveforms needed in many applications.

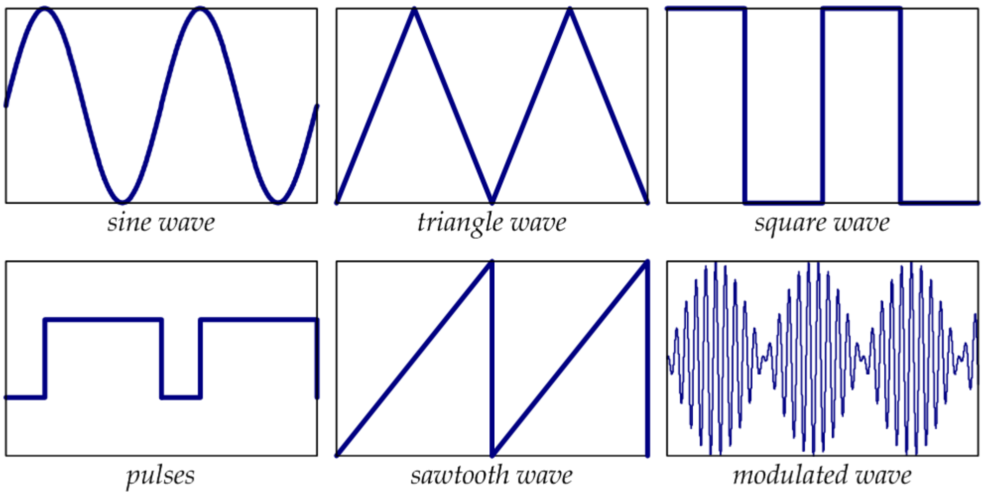
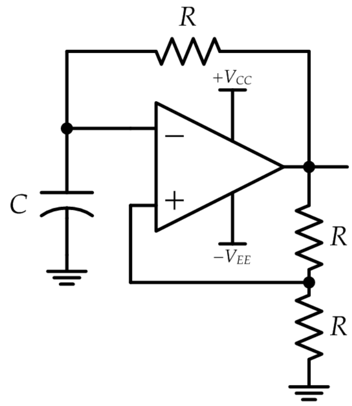
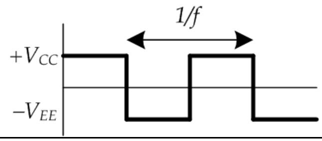


Figure (1): Examples of different waveforms

The following circuits produce different waveforms with specific features as described.

Square Wave Generator



Function:	generates square wave with certain frequency and amplitude
Use:	transmitters/receivers, digital communications
Design Equations:	$f \approx \dfrac{1}{2.2\,RC}$ Hz 

Example:

A square wave signal is needed with 120 Hz, ±10V peak voltages.

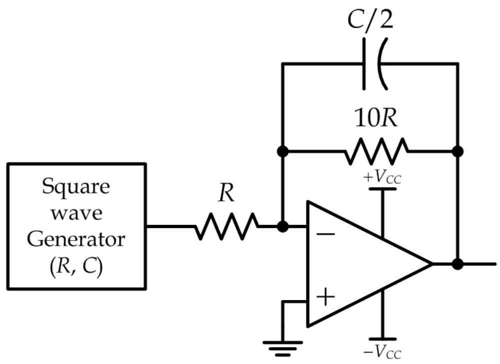
Design:

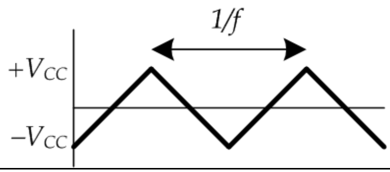
We assume a capacitor of 0.1μF. The resistors of the circuit will be:

$$f \approx \frac{1}{2.2\,RC} \rightarrow R = \frac{1}{2.2C\,f} = 37.9k\Omega$$

For the op-amp supplies, use LM741 and supply it with ±12V to guarantee ±10V.

Triangular Wave Generator



Function:	generates triangular wave at certain frequency and amplitude
Use:	power supplies, induction motor controllers
Design Equations:	$f \approx \frac{1}{2.2\,RC}$ 

Example:

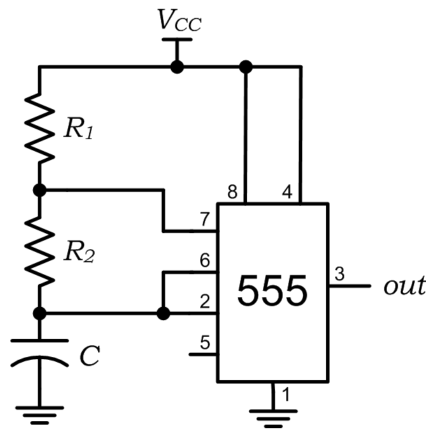
Design a triangular wave generator with peak voltage of ±10V and a frequency of 120 Hz.

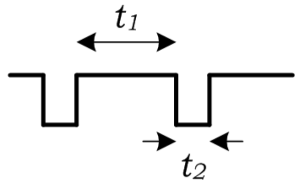
Design:

We first design a square wave generator with the required specifications (same frequency and amplitude), which gives C=0.1μF and R=37.9kΩ.

Then, we need to have $C/2$=0.05μF capacitor and *10 R*=379kΩ resistor at the second stage of the circuit.

Pulse Generator



Function:	generates digital pulses with specific durations
Use:	servo motor driver, modulation, control circuits
Design Equations:	$t_1 = \ln 2 \times (R_1 + R_2) \times C$ $t_2 = \ln 2 \times R_2 \times C$  The frequency $f = \dfrac{1}{t_1 + t_2}$ The duty cycle $D = \dfrac{t_1}{t_1 + t_2}$

Example:

Design a circuit that generate pulses of 20µs ON and 5µs OFF (or a 40 kHz clock with 80% duty cycle).

Design:

We set: t_1=20µs, and t_2=5µs. Hence,

$$R_1 + R_2 = \frac{20 \times 10^{-6}}{\ln 2 \times C}$$

$$R_2 = \frac{5 \times 10^{-6}}{\ln 2 \times C}$$

Now we choose a reasonable value for C in the range 10pF to 10µF, and check that the resistors values are reasonable too (100Ω to 100kΩ).

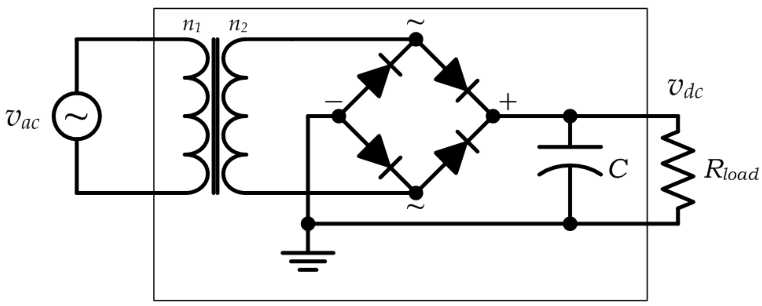
Setting C to 10pF yields R_2=721kΩ and R_1=2.16MΩ, which are not suitable resistor values. Thus we should choose a higher C value. Let C = 1nF, thus:

C = 1nF R_2 = 7.21 kΩ R_1 = 21.6 kΩ

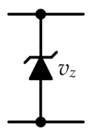
Converters

Converters, or sometimes called inverters, are used in many applications. Conversion types include altering between AC and DC power, DC to DC level changes, analog and digital, voltage and current, frequency and voltage, and so on. Books on power electronics cover a wide range of these converters. However, in the coming sections, we will show samples of these converters with basic working designs at comprehension level.

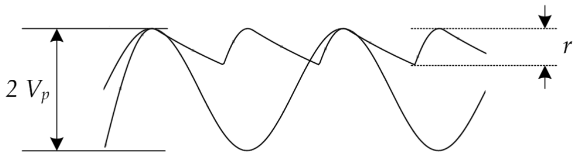
AC-to-DC Converter



DC Rectifier



Extra Smoothing Stage

Function:	generates DC power from an AC source
Use:	adopters of most electronic devices (laptops, video games, printers, amplifiers, etc.)
Design Equations:	DC Output: $v_{dc} = V_p \dfrac{n_2}{n_1} - 2 \cdot V_D$ Ripples: $r \approx \dfrac{v_{dc}}{2 \cdot f \cdot C \cdot R_{load}}$ V  An additional smoothing zener diode can be added for better DC output; however, it's breakdown voltage must match the exact DC output needed; $v_z = v_{dc}$

Example:

Design a mobile charger of 5V, 4W fed from a mains power supply of RMS voltage of 115V. The ripples in the DC voltage should not exceed 5%.

Design:

From the power rating, we calculate the maximum load current as: $P = I_L \times v_{dc}$, and the load current is I_L = 800mA. The diode bridge must be able to handle such current. A good distributor of electronic components is www.digikey.com. Search for *bridge rectifiers* and filter the selection to ensure a minimum of 800mA rating (or better 1A), a minimum of 5V rating or higher.
A possible selection could be:

DIODE SCHOTTKY 1A 20V MBS-1 (MB12S-TPMSDKR-ND)

To find out the forward voltage of the diode we must look at the datasheet of the component. For the item we selected (MB12S), V_D=0.5V.

The peak AC voltage is:

$$V_p = \sqrt{2} \times V_{rms}$$

The transformer ratio can then be found as:

$$v_{dc} = V_p \frac{n_2}{n_1} - 2 \cdot V_D$$

And the transformer ratio is about 27:1. Searching for a transformer with the required specs, we found the part number “166J5”.

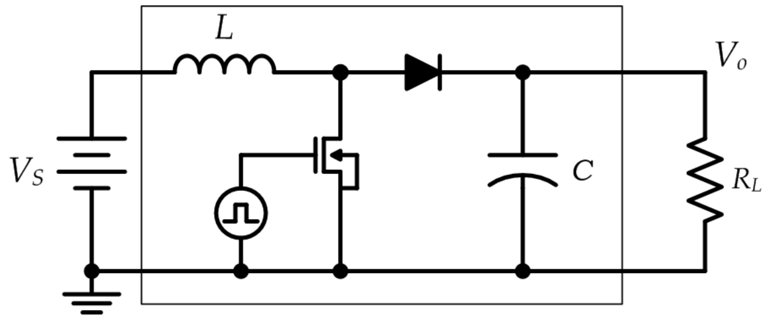
Finally, we choose a capacitor that ensures smooth DC output within the ripples allowed. We need r and R_L in the equation:

$$r = \frac{5}{100} \times 5 = 0.25V$$

$$P_L = \frac{v_{dc}^2}{R_L} \rightarrow R_L = \frac{25}{4} = 6.25\Omega$$

Thus, C_{min} = 26.6 mF. Since capacitors have high tolerance values (10% to 25%), we increase the value 25% more and search for the nearest value in market. The capacitor value is 35mF with a voltage rating 5 times the maximum (25V). The item number in Digikey is CGS353U040V5L-ND.

DC-to-DC Converter



Function:	boosts up the DC level of a source
Use:	adopters, multiple DC rating systems
Design Equations:	pulse generator duty cycle: $D = 1 - \frac{V_S}{V_o}$ components: $L \geq \frac{D(1-D)^2}{2f} R_L$ $C \geq \frac{V_o}{r \cdot f \cdot R_L}$ Note that the diode and the inductor must be able to handle a peak current of: $I_{peak} = \frac{D \cdot V_S}{f \cdot L}$

Example:

Design a 10W regulator to produce 20V out of 5V DC with ripples below 1%.

Design:

The duty cycle of the pulse generator must be:

$$D = 1 - \frac{V_S}{V_o} = 1 - \frac{5}{20} = 75\%$$

Let's set the clock frequency to f = 10 kHz as a starting point.

Now since the regulator load will consume 10W at 20V, then the worst load will be:

$$P = \frac{V_o^2}{R_L} \rightarrow R_L = 40\Omega$$

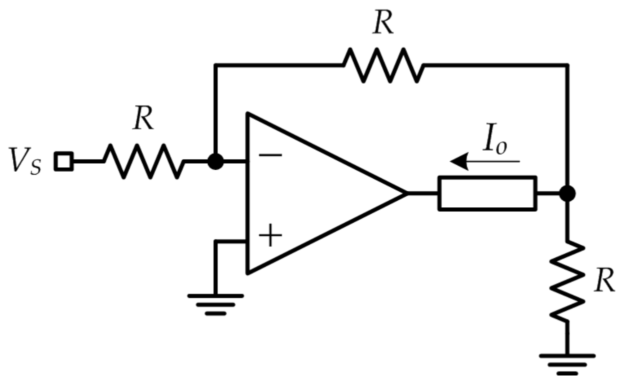
The components can then be calculated:

$$L \geq \frac{D(1-D)^2}{2f} R_L = 94\mu H$$

$$C \geq \frac{V_o}{r \cdot f \cdot R_L} = 2500\mu F$$

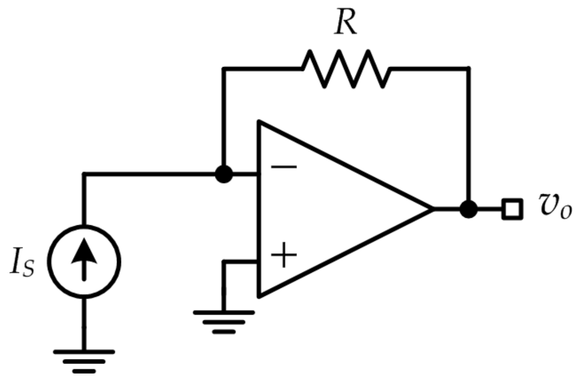
The components are in the acceptable range; otherwise, we should change the clock frequency.

Voltage-to-Current Converter



Function:	converts voltage signal to current with same waveform
Use:	actuators drivers, current sources
Design Equations:	$I_o = \frac{2}{R} \cdot V_S$

Current-to-Voltage Converter

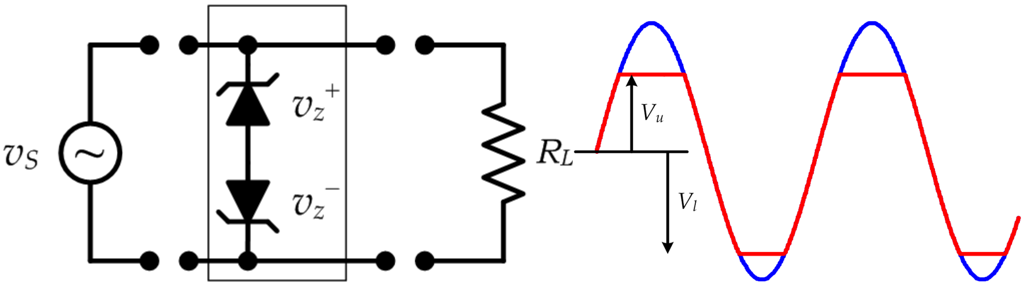


Function:	converts generated currents to voltage signal
Use:	current sensors interface and buffer
Design Equations:	$v_o = R \cdot I_S$

Protection Circuits

Mistakes happen in many occasions while operating electronic devices: plugging a 110V machine into a 220V power supply, using weak cord extensions to supply high power machines, or reversing a battery poles while charging a car battery. Electronic devices especially the expensive ones need protection against common mistakes. In this section, we present basic and simple interface protection circuits against high voltage, high currents, and reverse polarity in DC supplies.

Voltage Clipping



Function:	limits the voltage levels to an upper and lower limits
Use:	preventing input channels from over-voltage, electro-static discharge (ESD) protection
Design Equations:	each zener diode has: 1. a forward voltage, V_f (typically 0.7V) 2. a breakdown voltage, V_z such that: $V_u = V_z^+ + V_f^-$ $V_l = V_z^- + V_f^+$

Example:

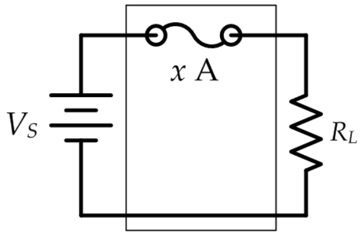
Design a clipping protection circuit to limit the input voltage to -3.2V to +5.4V.

Design:

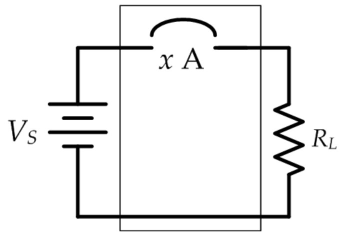
Since we can't know the forward voltage of the other diode before selecting it, we assume 0.7V and select the two diodes, and later we fine adjust them.

- For the upper level, we need a zener diode with $V_z^+ = 5.4 - 0.7 = 4.7V$
- For the lower level we need a zener diode with $V_z^- = 3.2 - 0.7 = 2.5V$

Current Limiters



fuse protection



circuit breaker protection

Function:	limits the supplied current to a certain ampere
Use:	house mains supply, most of auxiliary equipment
Design Equations:	choose the suitable rating

Example:

A 1100W vacuum cleaner operating at 220V~ volte needs a circuit breaker protection. What is the current rating of the breaker?

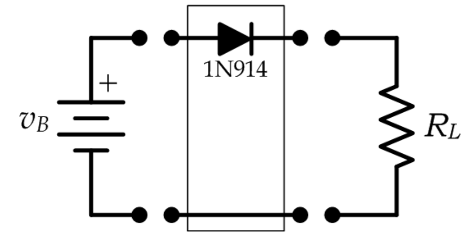
Design:

From the power consumption of the machine and the voltage rating, we estimate the maximum current drawn the supply as:

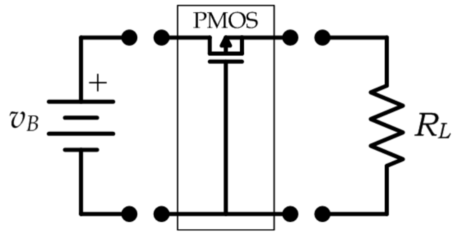
$$P = I \cdot V \rightarrow I = \frac{1100}{220} = 5A$$

Choosing an exact 5A circuit breaker might cause a problem of breaking the supply at any change in the voltage from the source. Thus it is recommended to choose a bit higher rating breaker, say 5.5A to prevent frequent interruptions.

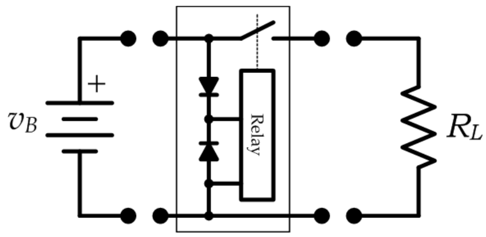
Reverse Polarity Protection



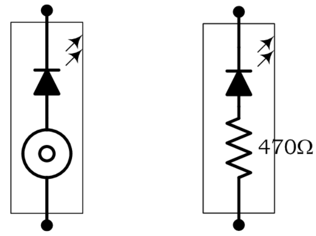
(a) diode protection



(b) MOSFET protection



(c) relay protection

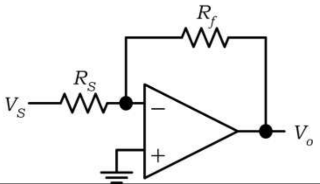
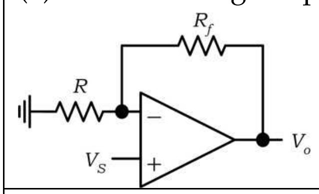
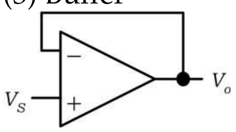
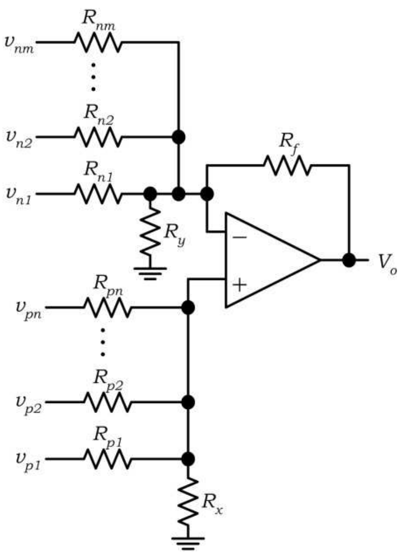


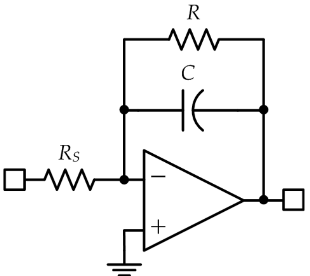
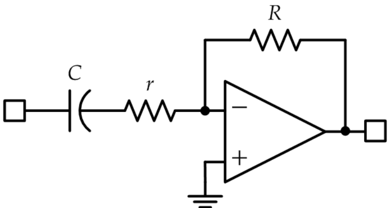
(d) optional indicators

Function:	discontinues power when incorrectly installed batteries
Use:	powering circuits with op amps, transistors, ICs, alternators
Design Equations:	• components must be able to handle the voltage v_B, and the maximum load current: $$I_L \approx \frac{v_B}{R_L}$$ • in configurations (a) and (b), a voltage drop will be introduced, thus the load might not have the full power • optional indicators can be installed for more protection at the front stage

Math Circuits

In many applications, mostly in controlling and processing analog signals, manipulations of signals such as amplifications, additions, subtractions, integrations, and differentiations are required. The following basic building blocks use op-amps as the main active components in the design. Beware that op-amps need to be powered correctly by dual DC supplies, which are not shown in the designs below for simplicity.

(1) Inverting Amplifier 	signal amplification with negative gain: $V_o = -\frac{R_f}{R_S} V_S$
(2) Non-inverting Amplifier 	signal amplification with positive gain: $V_o = \left(1 + \frac{R_f}{R}\right) V_S$
(3) Buffer 	buffering the source: $V_o = V_S$ $R_{in} = \infty$
(4) General Mixer 	mixing signals with different weights: $V_o = \sum_{i=1}^{n} A_i v_{pi} - \sum_{i=1}^{m} B_i v_{ni}$ where, $A_i = \frac{R_f}{R_{pi}}, B_i = \frac{R_f}{R_{ni}}$ $A = \sum A_i, B = \sum B_i$ $C = A - B - 1$ $\begin{cases} C \geq 0 & R_x = \infty & R_y = \frac{R_f}{C} \\ C < 0 & R_x = -\frac{R_f}{C} & R_y = \infty \end{cases}$

(5) Integrator 	Can't Integrate Low Frequencies: $v_o = \begin{cases} -\dfrac{R}{R_S} & f \le f_0 \\ -\dfrac{1}{R_S C}\int v_s(t)\,dt & f > f_0 \end{cases}$ where, $f_0 = \dfrac{1}{2\pi RC}$
(6) Differentiator 	Can't differentiate high Frequencies: $v_o = \begin{cases} -RC\dfrac{d}{dt}v_s(t) & f \le f_0 \\ -\dfrac{R}{r} & f > f_0 \end{cases}$ where, $f_0 = \dfrac{1}{2\pi rC}$

Example:
Design a mixer that implements $8v_a + 6v_b + 3v_c - 7v_1 - v_2 - 5v_3$ and integrate the output signal given that it does not contain frequencies below 10 Hz.

Design:
We have the following positive and negative gains: A_1=8, A_2=6, A_3=3, and B_1=7, B_2=1, B_3=5. From which $C = A$-B-1 = (8+6+3)-(7+1+5)-1 = 3 ≥ 0. Let's use R_f = 120kΩ, then we can calculate all the resistors as follows:

$$\begin{cases} R_a = 15k\Omega & R_1 = 17.14k\Omega & R_x = \infty \\ R_b = 20k\Omega & R_2 = 120k\Omega & R_y = 40k\Omega \\ R_c = 40k\Omega & R_3 = 24k\Omega & \end{cases}$$

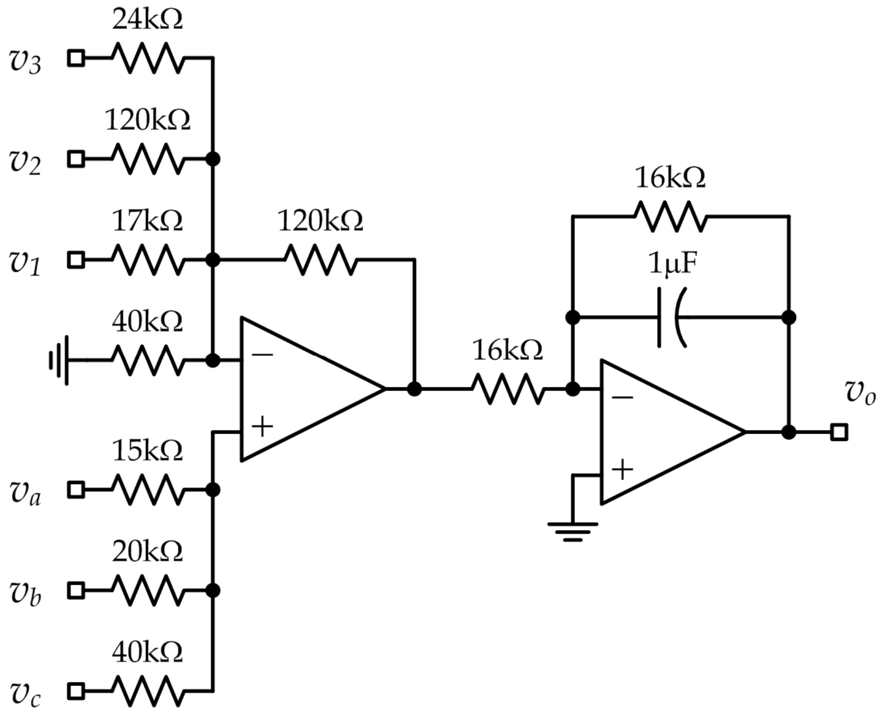
For the integrator, we should have:

$$f_0 = \frac{1}{2\pi RC} = 10 \rightarrow RC = 0.016$$

Choosing C=1μF we get R=16kΩ. We might choose the same resistance for R_S = 16kΩ, which will make the integration constant:

$$-\frac{1}{R_S C} \approx -63$$

Finally, the total design of the integrating mixer will be:



$$v_o = -63\int\left(8v_a + 6v_b + 3v_c - 7v_1 - v_2 - 5v_3\right)dt$$

Filters

Analog real signals have certain shapes in the time domain. Human voices can be converted into voltage signals using microphones, which can then be plotted with respect to time. In human voices, we hear different tones; this translates to signals with multiple frequencies. Consider the simple waveform shown in Figure (1).

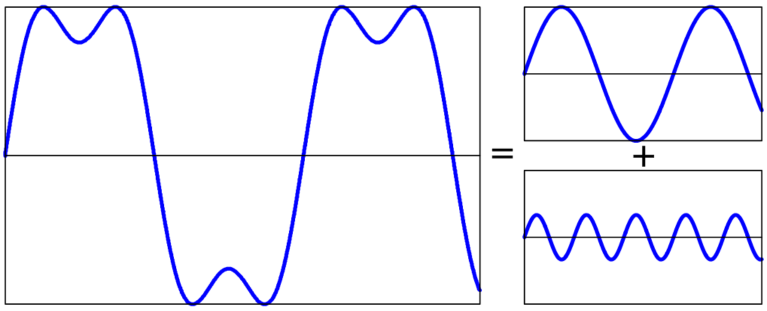


Figure (1): Waveform decomposition example

The original signal can be *decomposed* into two fundamental sine waves with different frequencies and certain amplitudes. If you happen to have a *filter* that is capable of removing the higher frequency tone, then this filter is called a *low pass filter* meaning it passes only the low frequencies of the signal and blocking the higher ones. Consequently, all signals can be decomposed into multiple fundamental sinusoids, and if you draw the amplitudes of the decomposed signals versus frequency you get the *frequency spectrum* of the signal as shown in Figure (2):

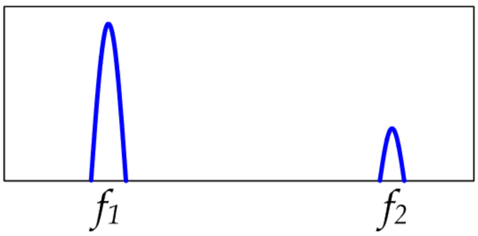


Figure (2): Frequency spectrum of the previous waveform

The filtering operation is better viewed in the frequency domain rather than time. In general, there are four different types of filters depending on what range of frequencies they pass or stop, see Figure (3):

1. **Low Pass Filters**: where all the low frequencies from 0 up to certain cut-off frequency f_0 will be passed
2. **High Pass Filters**: where all the low frequencies from 0 to f_0 will be stopped and all other frequencies from f_0 and up are passed
3. **Band Pass Filters**: where the frequency range from f_1 to f_2 will only be passed
4. **Band Stop Filters**: where the frequency range from f_1 to f_2 will be stopped

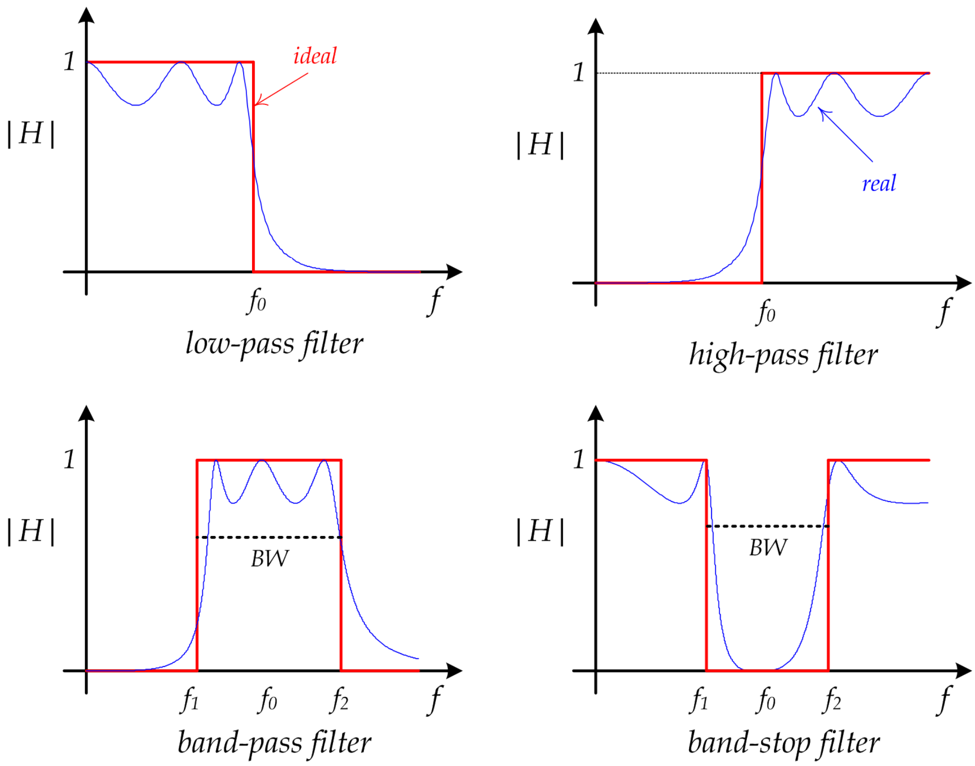
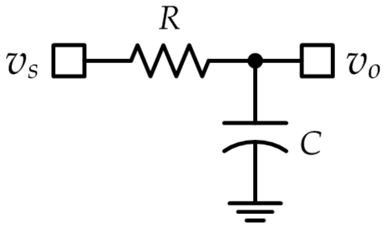
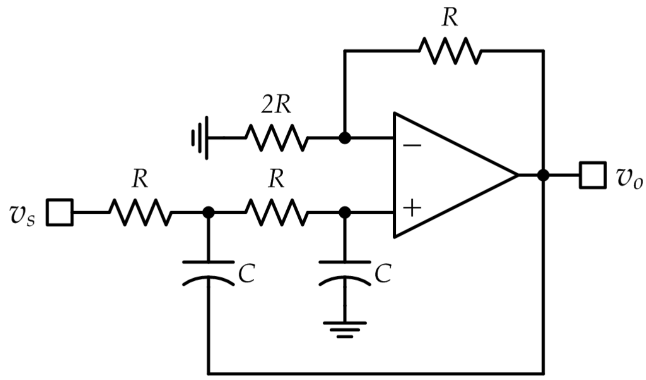


Figure (3): Types of filters

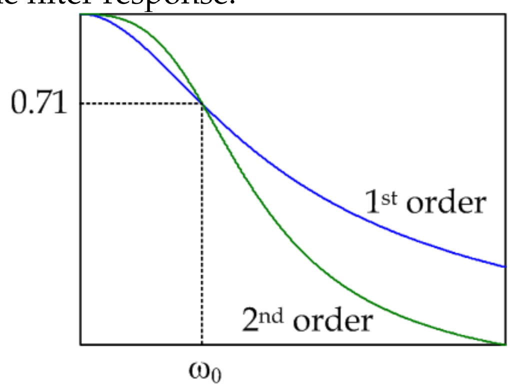
Low Pass Filters



1st order LPF



2nd order LPF

Function:	low pass filter
Use:	communications, sensors interfaces
Design Equations:	the cutoff frequency of the filter is at: $$\omega_0 = \frac{1}{RC}$$ with the filter response: 

Example:

Design a 2nd order filter to stop frequencies above 10 kHz.

Design:

We need a 2nd order low pass filter with a cutoff frequency of:

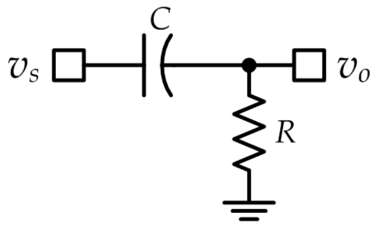
$$\omega_0 = 2\pi f_0 = 62{,}832 \ rad/s$$

Choosing a capacitor of C=1nF gives:

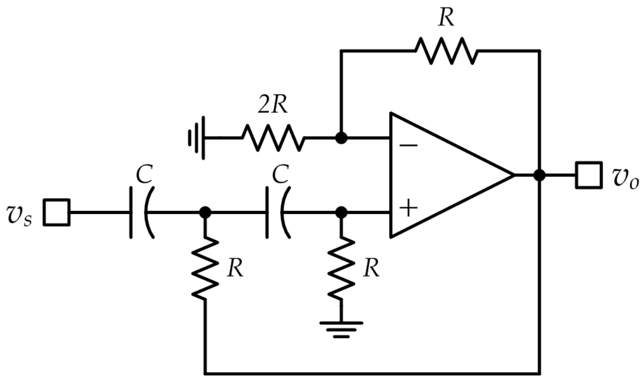
$$\frac{1}{RC} = \omega_0 \rightarrow R \approx 16\text{k}\Omega$$

Thus, we need two capacitors each of 1nF, three resistors each of 16kΩ, one 32kΩ resistor, and an op-amp.

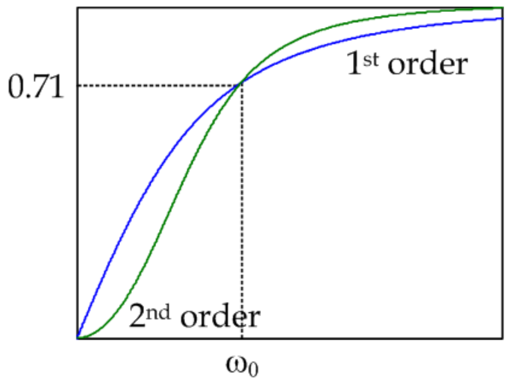
High Pass Filters



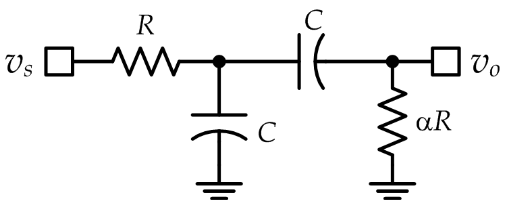
1st order HPF



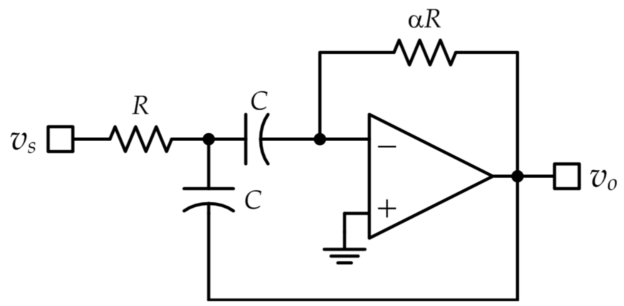
2nd order HPF

Function:	high pass filter
Use:	communications, DC blocks, offset nulling
Design Equations:	the cutoff frequency of the filter is at: $$\omega_0 = \frac{1}{RC}$$ with the filter response: 

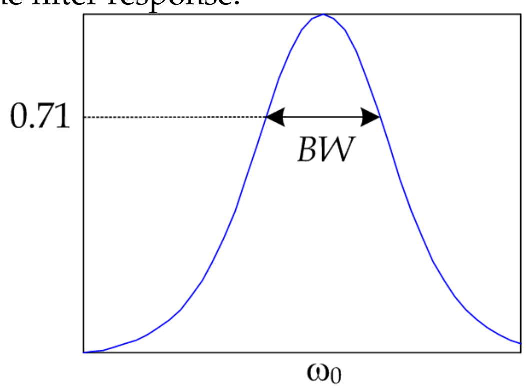
Band Pass Filter



Passive BPF



Active BPF

<table>
<tr><td>Function:</td><td colspan="2">band pass filter</td></tr>
<tr><td>Use:</td><td colspan="2">communications for channel selection</td></tr>
<tr><td rowspan="3">Design Equations:</td><td colspan="2">the cutoff frequencies and band widths of the filters are:</td></tr>
<tr><td>passive equations:
$$\omega_0 = \frac{1}{RC\sqrt{\alpha}}$$
$$BW = \frac{2+\alpha}{\alpha RC}$$
for design, use:
$$\alpha \approx \frac{\omega_0}{2\cdot BW - 5\cdot\omega_0}$$
$$RC = \frac{1}{\omega_0\sqrt{\alpha}}$$</td><td>active equations:
$$\omega_0 = \frac{1}{RC\sqrt{\alpha}}$$
$$BW = \frac{2}{\alpha RC}$$
for design use:
$$\alpha = \frac{4\cdot\omega_0^2}{BW^2}$$
$$RC = \frac{1}{\omega_0\sqrt{\alpha}}$$</td></tr>
<tr><td colspan="2">with the filter response:

</td></tr>
</table>

Example:

Design a band pass filter at 10kHz center frequency and a bandwidth of 5kHz.

Design:

We start with the passive design because it is cheaper. We have:

$$\begin{aligned} \omega_0 &= 2\pi \cdot f_0 &&= 62{,}832 \\ BW &= 2\pi \cdot 5{,}000 &&= 31{,}416 \end{aligned}$$

From the design equations of the passive BPF, we find:

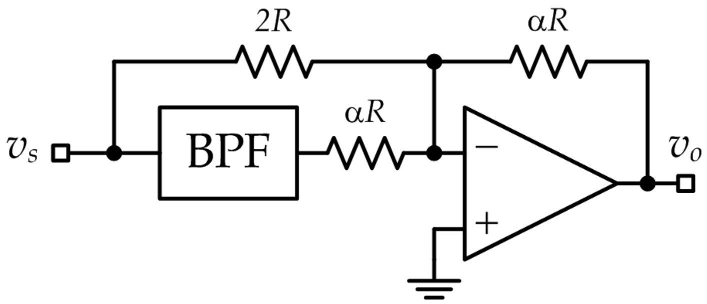
$$\alpha \approx \frac{\omega_0}{2 \cdot BW - 5 \cdot \omega_0} = -0.25$$

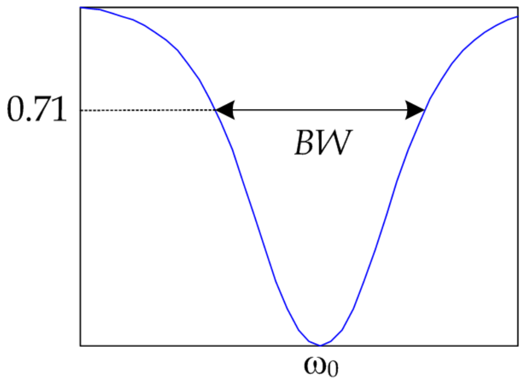
which is impossible to build. Thus, we must use the active BPF as follows:

$$\begin{aligned} \alpha &\approx \frac{4 \cdot \omega_0^2}{BW^2} &&= 16 \\ RC &= \frac{1}{\omega_0 \sqrt{\alpha}} &&= 3.98 \times 10^{-6} \end{aligned}$$

Choosing C=1nF gives R≈4kΩ, and αR=64kΩ.

Band Stop Filter



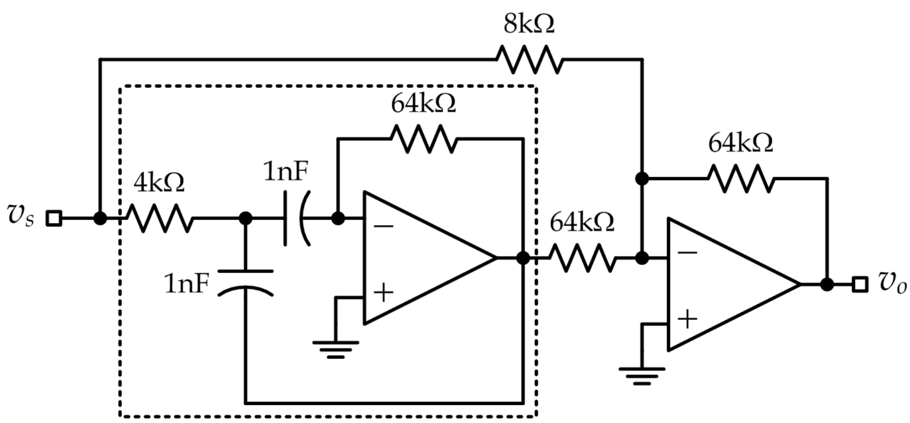
Function:	band stop filter or notch filter
Use:	communications, channel rejection, noise rejection
Design Equations:	the same design equations of the 2nd order BPF with the filter response: 

Example:

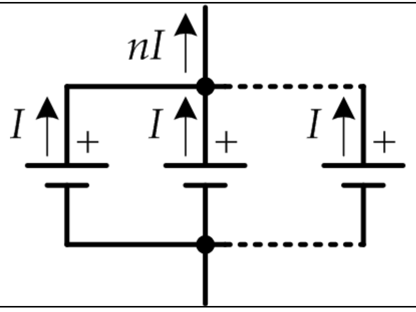
Design a band stop filter at 10kHz center frequency and a bandwidth of 5kHz.

Design:

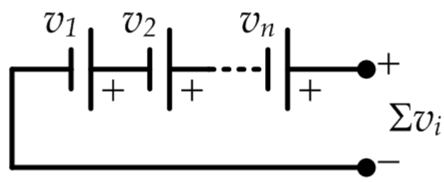
We design an active band pass filter first, which gives C=1nF and R≈4kΩ, and αR=64kΩ. We just need three extra resistors with values of αR and 2R≈8kΩ as shown:



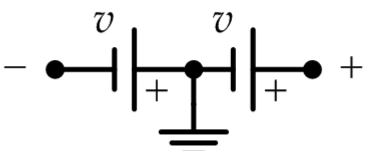
DC Supplies



(a) Higher Current



(b) Higher Voltage

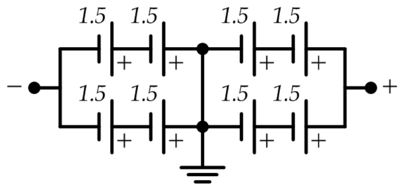


(c) Dual Supply

Function:	DC sources arrangements
Use:	more current capacity for large power consuming loads, more voltage potential, dual supply requirements in many op amp circuits
Design Equations:	a. $I_{total} = n \times I_s$ b. $v_{total} = \sum_{i=1}^{n} v_i$ Battery Capacity is expressed in Ampere-Hours (AH) in terms of maximum current as: $AH = 20 \times I_{\max}$

Example:

Design a ±3V dual supply voltage with a current capability of 0.5A using batteries of 1.5V with 5Ah.



Answer:

- Each battery can supply: $I_{\max} = \frac{5}{20} = 0.25A$
- We need $\frac{0.5A}{0.25A} = 2$ parallel batteries to supply 0.5A
- We need $\frac{3}{1.5} = 2$ cascaded batteries to produce 3V
- We need $2 \times 2 = 4$ batteries to supply 3V with 0.5A current
- We need another 4 batteries for the negative voltage, -3V

References

1. freecircuitdiagram.com
2. www.discovercircuits.com
3. www.allaboutcircuits.com
4. www.ladyada.net