ASSIGNMENT 9

Due date: Nov 25, 2025 (4 PM)

Unless otherwise indicated all op amps are ideal.

Relevant Class Notes	**Assessment Criteria**
Frequency Domain Representations (§5.3) Noise Management (§ 5, 7, 8, 9) Signal Digitization (§3.5.2) Data Conversion (§ 2, 4.2, 5)	Write a MATLAB script to analyze a problem. Apply one or more procedure(s) to a problem. Analyze a problem and obtain a correct result. Provide short answers to questions.
References to Prior Assignments	
Q1 builds upon Assignment 1 Q4. Q3 build upon Assignment 6 Q3 & Assignment 8 Q2.	

Manage your time. Having problems with the assignment? Discuss them with the instructor!

Attachment09.zip accompanies this assignment and contains needed MATLAB files

1. (2.5/10)

Generating spectrally-pure sinusoidal waveforms is challenging. However, for applications where a signal that looks sinusoidal suffices, one may use the technique shown in Figure 1.

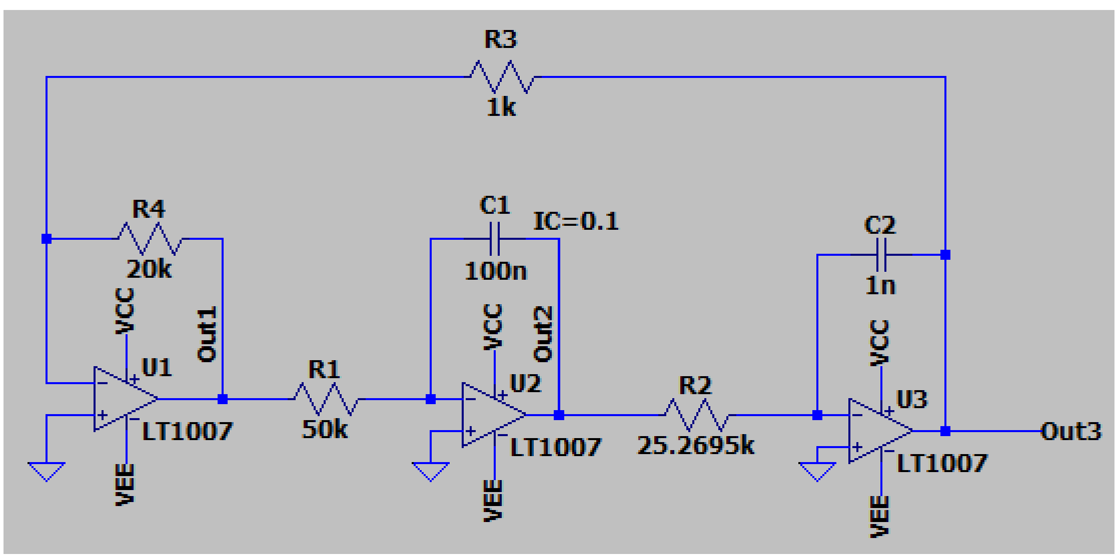


Figure 1. A non-linear oscillator implements a waveform generator. U1, R3 and R4 form an inverting amplifier with sufficient gain to cause Out1 to saturate, resulting in a square-wave-like signal. U2, R1, C1 and U3, R2, C2 each implement an inverting integrator that double-integrate the square wave. The system output, Out3, is fed back to the U1, completing a loop. The initial condition on C1 starts the circuit in the case of simulations. In real life, start-up transients start the oscillator when power is applied.

Figure 2 shows 8ms of simulation in steady state. The red curve is Out3 and appears sinusoidal and has a fundamental frequency of 500Hz.

The accompanying zip file contains *Q1.mat*, containing an ample amount of data, where *t* is time (seconds), *Vout3* is Out3 (volts).

In real-world applications, where the period of a signal is not an integer multiple of the sampling time (all the time), efforts are made to minimize spectral leakage resulting from discontinuities between the signal endpoints, as a result of the data segment periodicity assumed by the DFT algorithm. See *Q1_primer.m* to see how "windowing" plays into this.

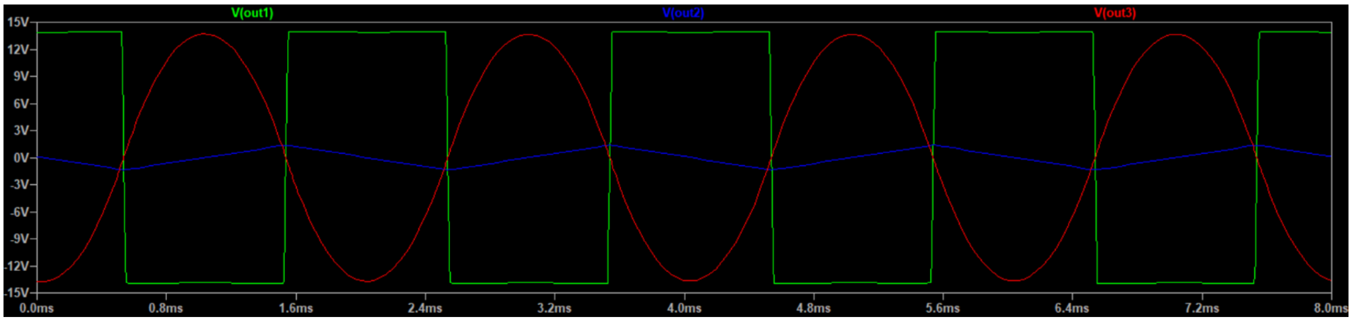


Figure 2. Simulation showing output from U1 (square, green), U2 (triangle, blue), and U3 (parabola, red) waveforms.

Use MATLAB to compute the Total Harmonic Distortion (THD) of *Vout3* over 7 harmonics, thereby quantifying the purity of the 'sinusoid'. Submit your MATLAB code.

- Produce a plot of the magnitude frequency spectrum with the vertical axis in dB (linear frequency)
- Identify the harmonics used in the THD calculation by (manually) adding Data Tips to the plot

2. (1.5/10)

a) How does the use of shielded twisted-pair wire help to address the problem of capacitively-coupled noise?

b) Does the use of shielded twisted-pair wire help to address the problem of magnetically-coupled noise?

- If so, briefly discuss the roles of the shield and wire twisting.
- If not, then briefly discuss why not.

c)

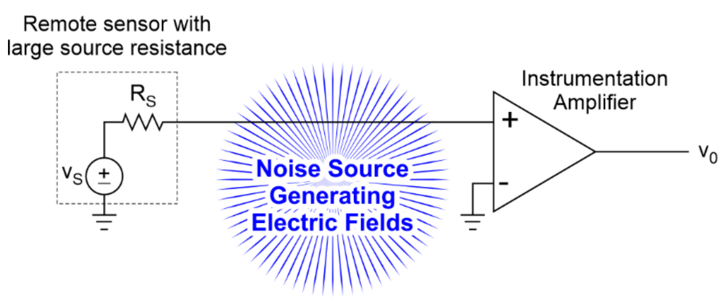


Figure 3

Figure 3 shows a remote high-impedance sensor connected to an amplifier with high input-impedance. Other than shielding the connective wires, what other technique may be used to address the problem of capacitively-coupled noise?

3. (4/10)

Figure 4 shows part of a data conversion system: an anti-aliasing filter driving an ADC. (The S&H module has been omitted.)

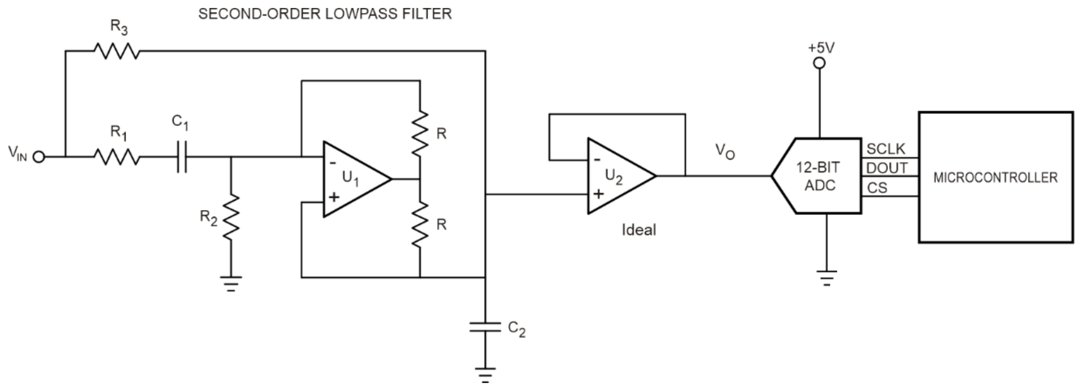


Figure 4

The above system may be represented by the block diagram in Figure 5. (See text for v_n.)

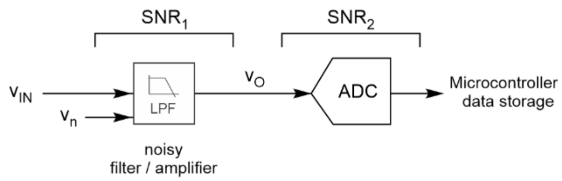


Figure 5

The ADC has an input range of 0V to 5V and a typical SNR specification of 73.2dB. The filter component values, supplied in *Q3component.mat*, realize a Butterworth response with a gain of 50 and a bandwidth of ~100Hz. (For reference, *Q3TF.m* evaluates the ideal filter transfer function, $V_O(s)/V_{IN}(s)$.)

In an optimal design the filter characteristics are matched to the abilities of the ADC. In practice several filter specifications would be considered (some not covered in the course). In this question you will only consider the filter's output noise caused by U_1; for simplicity resistor noise will be ignored and U_2 will be taken to be ideal.

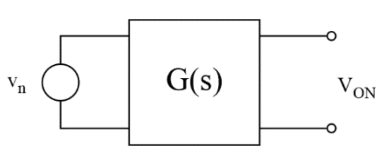
A CMOS op amp is used having insignificant current noise, leaving only voltage noise (v_n) to be studied. We will also assume that v_n is white because this is a wide-band application.

The op amp has a GBW = 1.2MHz, dc gain of 90dB, and a rail-to-rail output swing.

MATLAB is able to solve a system of transfer functions just as easily as a system of linear equations. Once the matrices have been set up, the syntax for solving the system of transfer functions is identical to that for solving a system of linear equations. See the end of the assignment for an example. Stop hand calculations when MATLAB can take over the number crunching. Submit your commented M-file along with your solutions.

- You will eventually have to integrate an ugly expression. Do this numerically in MATLAB. The example *integration_demo.m* provided in *MyCourses* under *Course Content > Reference Material > MATLAB Supporting Files* should prove helpful.

a)



Conceptually, the filter output noise, V_{ON}, is modelled as shown to the left, where $G(s)$ is due to the dynamic components in the system (including the op amp!) and, as such, is higher than 1st-order.

- Use MATLAB to analyze the circuit and compute $V_{ON}(s)/v_n(s)$.
  - Because of computational resolution, it will be necessary to force a pole/zero cancellation near the origin, otherwise the dc gain → ∞. The default *mineral()* will not work. You will have to use *mineral(●, tol)* with a specified tolerance (*tol*) because MATLAB's default tolerance is too small. Try *tol* = 1e-6.
- Use *bode* to plot the magnitude frequency response function of the resultant transfer function.
- What are the dc gain and bandwidth of this response?

b) Let V_{IN} be a sinusoidal waveform that uses the full ADC dynamic range. Use $G(s)$ determined above to compute the maximum v_n that will give an overall (filter + ADC) SNR that is 4dB lower than the ADC SNR.

- The sine wave will have a dc bias in order to match the dynamic range of the ADC. This bias contains no signal information and so should not be considered as signal power.
- Assume a linear system. Ignore that at maximum sine output that the additional noise will cause the output to clip.
- Though v_n is white, the NEB expression cannot be used; the rms output noise, needed to calculate amplifier SNR, must be determined by integration.

c) Assuming that THD = 0, what is the value of ENOB using the specification from part (c)? (Can be answered independently of results for (b).)

4. (2/10)

Figure 7 shows a high-level illustration of the instrumentation in a device that records and displays the pressure and flow of air delivered to each of two patients attached to a ventilator. The focus in the figure is power distribution. The system consists of:

- Boards 1 and 2: each a signal conditioning board that processes the flow and pressure signals, from one patient, and prepares the sensory signals for sampling.
- A touch display to interact with the device operator.
- Board 3: a microcontroller and user interface board that samples the signals from Boards 1 & 2, processes them, and displays the results on the touch display. (The logic level converter board is needed to allow the touch display to communicate with the microcontroller, as each operates at a different voltage level.)
- Power: two dedicated power supplies (PSU, 5V and 12V) for the sensors and microcontroller; the microcontroller generates 3V3 to power the signal conditioning electronics (op amps) on Boards 1 and 2.
  - The touch display draws 510mA of current from the 5V PSU (mostly dc current for the LCD backlight)
    - Tx and Rx are digital communication lines
  - A flow sensor can draw up to 20mA
  - A pressure sensor can draw up to 30mA
  - The microcontroller can draw up to 25mA
  - The logic-level converter module draws insignificant current

    - The signal conditioning electronics can draw 600µA per board

- The wires between the PSU units and the terminal barrier block are large conductors
- The distance between all boards and the terminal barrier block can be many centimeters, and are connected using wire typically used when wiring circuits (i.e., thin wires)

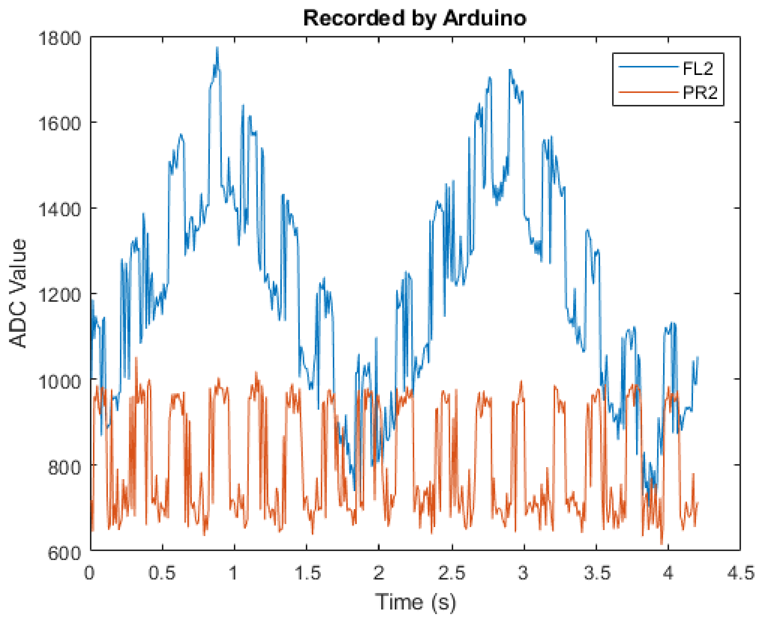


Figure 6. Two signals shown for clarity. Only sensor input *FL2* was excited; all other sensors were giving a baseline output and resulted in a recording similar to *PR2*.

Each signal conditioning board was tested by disconnecting a sensor and applying a triangular wave at the board input, emulating a sensor signal. The signals at the microcontroller ADC channels (A0, A1, A3, and A4) were measured with an oscilloscope and were found to be fine. However, the microcontroller recorded the signals shown in Figure 6. An unexpected square wave signal was superimposed on the desired sampled waveform.

It was also found that by decreasing the intensity of the LCD backlight (i.e., lowering the current draw) that the noise significantly improved.

Question: Propose a new wiring arrangement that will allow proper data acquisition. Briefly describe your analysis of the problem and your proposed solution. (If you elect to sketch something keep it simple. I do not need the same level of detail as shown in Figure 7.)

5. (2/10) Bonus

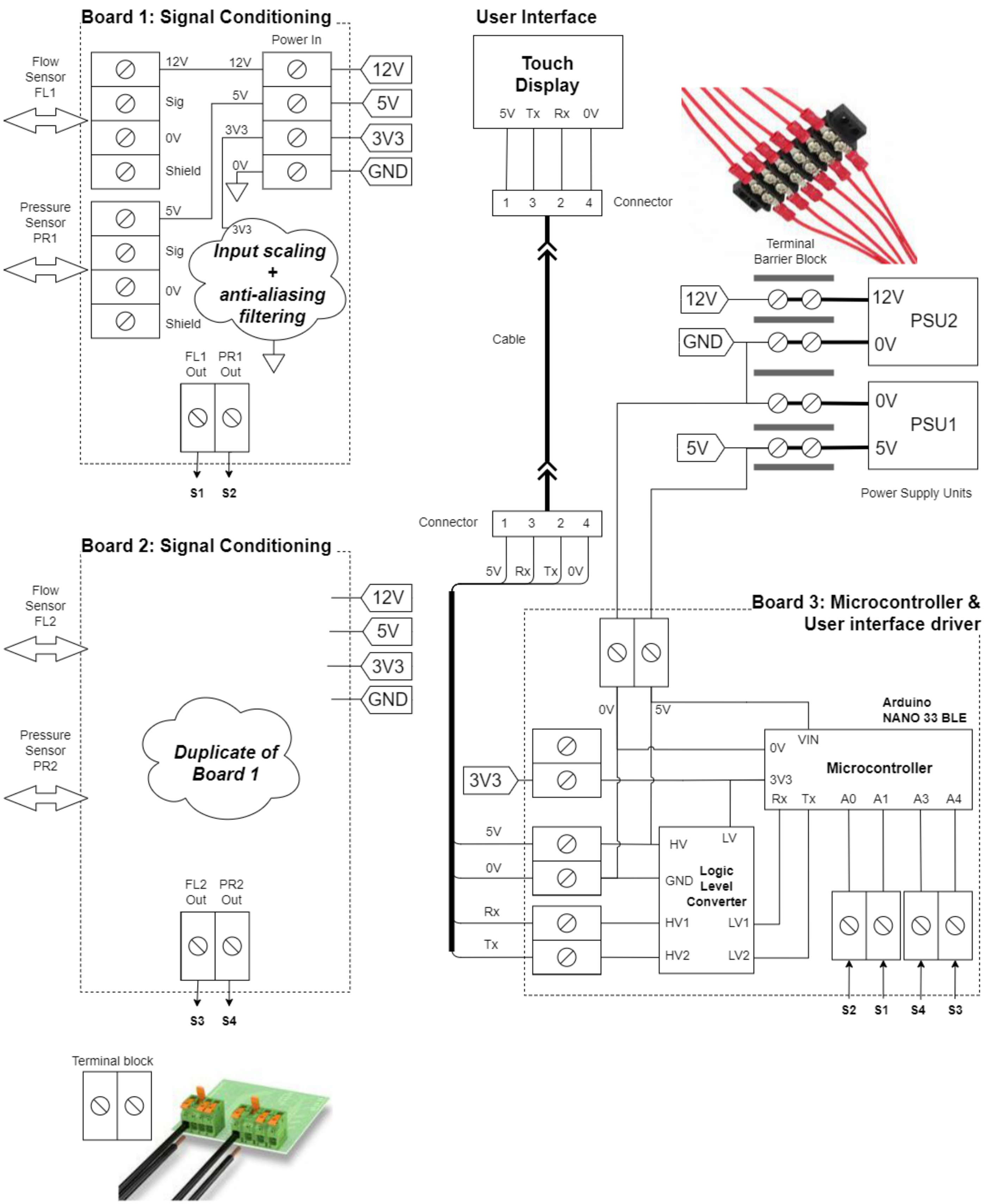
Please view the following short YouTube video entitled "Reasons to Complete your Course Evaluations".

a) What reasons were mentioned to complete your Mercury course evaluation?

b) What elements should a comment contain?

6. (0.5/10) Bonus

Report the amount of time spent on this assignment.



Board 1: Signal Conditioning
Power In
Flow Sensor FL1
12V
Sig
0V
Shield
12V
5V
3V3
0V
12V
5V
3V3
GND
Pressure Sensor PR1
5V
Sig
0V
Shield
3V3
Input scaling + anti-aliasing filtering
FL1 Out
PR1 Out
S1
S2
User Interface
Touch Display
5V Tx Rx 0V
1 3 2 4
Connector
Terminal Barrier Block
Cable
12V
PSU2
0V
GND
0V
PSU1
5V
5V
Power Supply Units
Connector
1 3 2 4
5V Rx Tx 0V
Board 2: Signal Conditioning
Flow Sensor FL2
12V
5V
3V3
GND
Pressure Sensor PR2
Duplicate of Board 1
FL2 Out
PR2 Out
S3
S4
Board 3: Microcontroller & User interface driver
0V
5V
Arduino NANO 33 BLE
0V
VIN
Microcontroller
3V3
Rx Tx A0 A1 A3 A4
3V3
5V
0V
Rx
Tx
HV
LV
GND
Logic Level Converter
HV1
LV1
HV2
LV2
S2 S1 S4 S3
Terminal block

Figure 7

Relevant MATLAB function(s):

dcgain	Computes the dc gain of a transfer function object.
bandwidth	Computes the bandwidth of a transfer function object. Units: rad/s.

Functions from previous assignments may also be useful.

Example

The following example illustrates how to solve a system of equations that contains Laplace variables without using the symbolic toolbox.

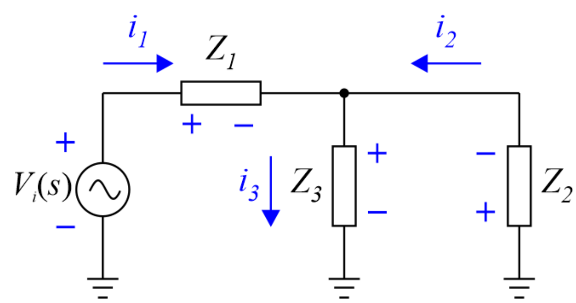
Let us find the voltage across Z_3 for the following case:

Z_1: 10nF capacitance (C_1)

Z_2: 10kΩ resistance (R_2)

Z_3: 10kΩ resistance (R_3)

$V_i(s)$ unit step



The resulting system is a high-pass system with time constant $C_1(R_1||R_2)$ = 50μs. The system equations are:

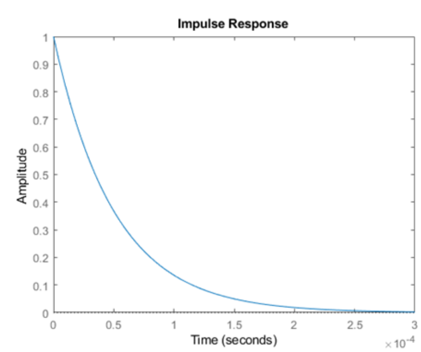
$$\begin{matrix} KCL \rightarrow \\ KVL \rightarrow \\ KVL \rightarrow \end{matrix} \begin{bmatrix} 1 & 1 & -1 \\ Z_1 & 0 & Z_3 \\ 0 & Z_2 & Z_3 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \begin{bmatrix} 0 \\ V_i \\ 0 \end{bmatrix} \qquad \text{where, } V_{Z_3} = i_3 Z_3.$$

The MATLAB code to solve for the step response, for example, is:

```
% Define the Laplace variable
s = tf('s');

% Define components
C1 = 10e-9;
R2 = 10e3;
R3 = 10e3;

Z1 = 1/(C1*s);
Z2 = R2;
Z3 = R3;

Vi = 1/s;   % Unit step input

% Set up the system of equations
A = [ 1  1 -1;
     Z1  0 Z3;
      0 Z2 Z3];

b = [0 Vi 0].';

% Solve for unknowns
x = A\b;

% VZ3(s)= i3 * Z3
VZ3 = minreal(x(3) * Z3, 1e-6)

% Time response over 6 time constants
impulse(VZ3, 6*50e-6)
```

Which yields:

```
VZ3 =

      1
  --------
  s + 2e04

Continuous-time transfer function.
```



impulse(●) can be used to determine the system response because VZ3 includes the system excitation. VZ3 is multiplied by unity (an impulse) then inverse-Laplace transformed.