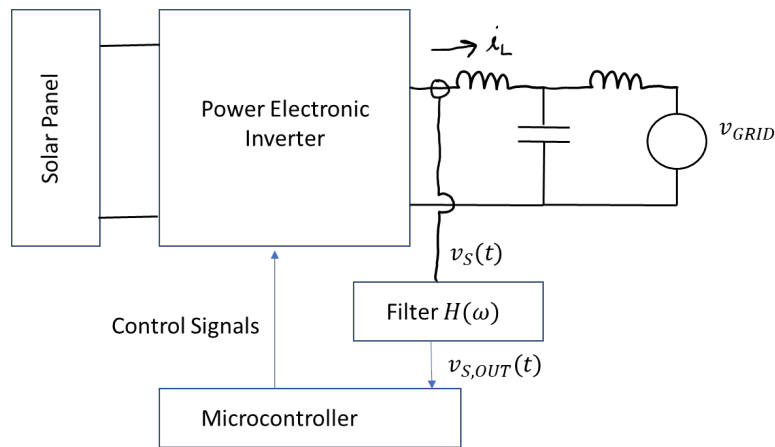
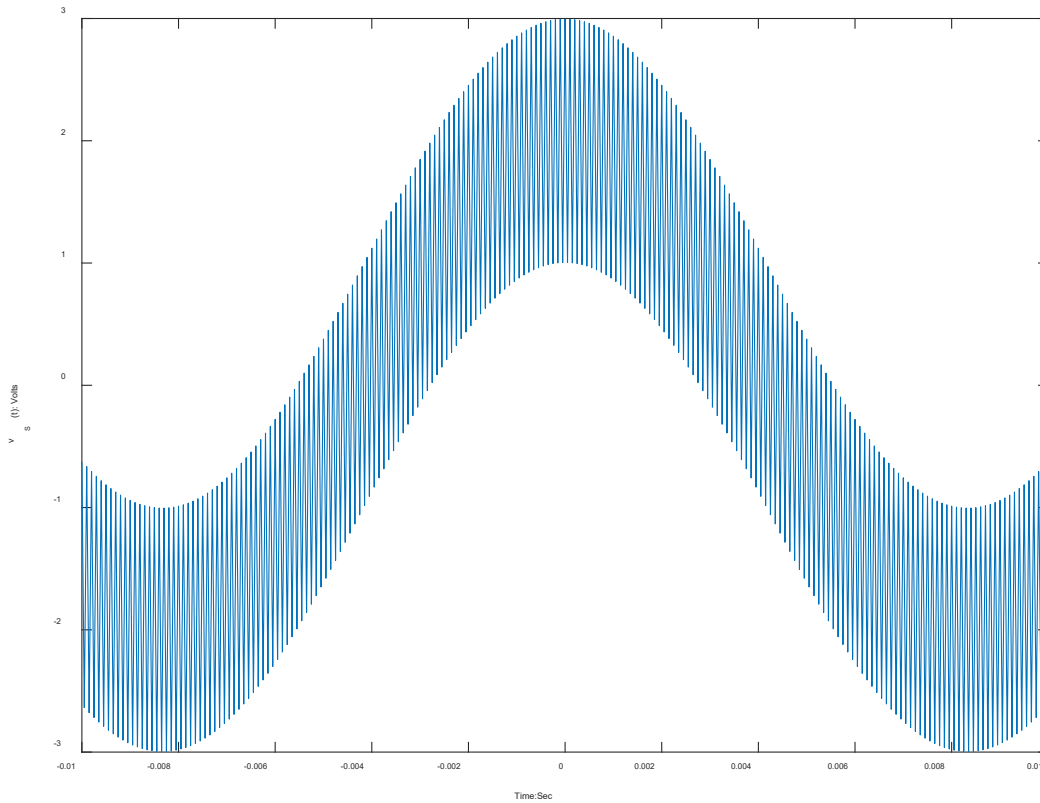


Due: 5/3/22 at 11:59PM

Problem 1 – Filtering a Signal for Control

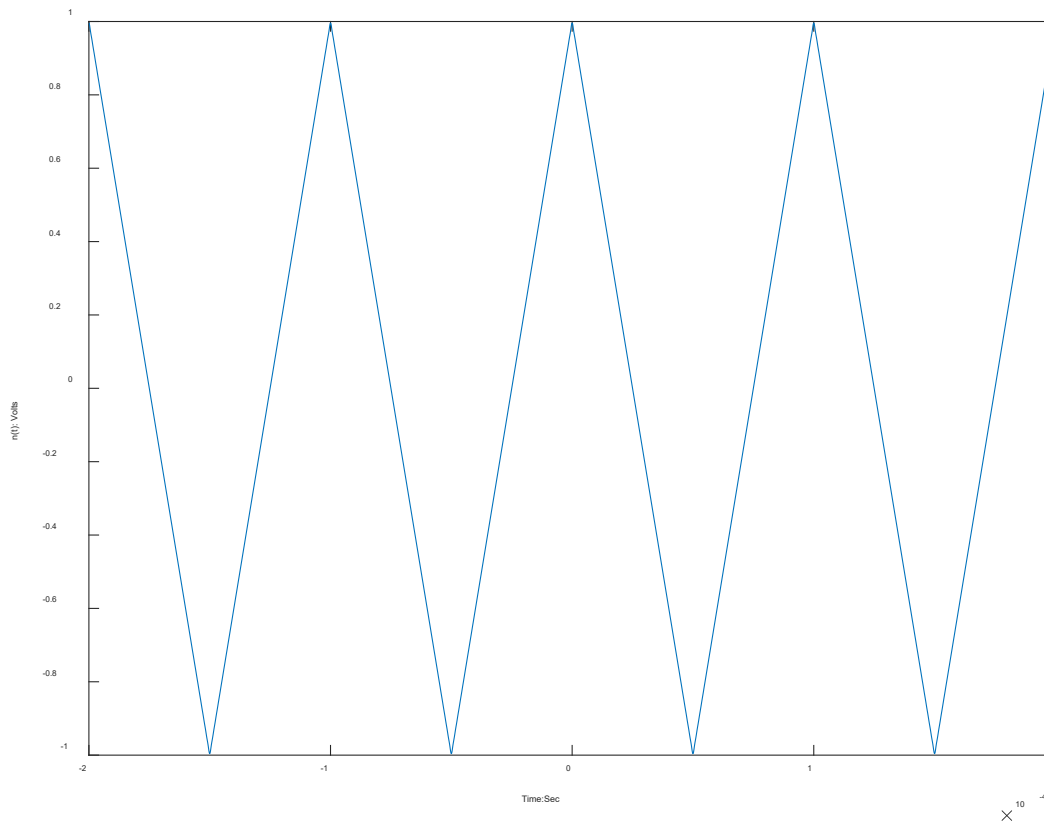
Solar panels are connected to the grid through a power-electronic inverter circuit that creates a sinusoidal current. An example system is shown in the figure below. Note that a current sensor measures the current $i_L(t)$ and converts it to an output voltage $v_S(t)$. An example version of this voltage $v_S(t)$ is also shown. Note that there is a 60Hz term added to a triangular signal. This triangular signal results from the action of the switches inside the inverter, and it is largely removed from the current as the signal passes through the LCL filter into the grid.





In a real control system, the signal $v_s(t)$ coming from the current sensor might be needed inside the microcontroller to be able to decide how to drive the switches. Typically, however, we only want the microcontroller to see the 60Hz signal and not the high-frequency triangle wave. To make sure this happens, we have added the filter $H(\omega)$, which would need to be constructed using op-amps, resistors, and capacitors. This is a common problem in embedded controls. Our goal here is to design the filter $H(\omega)$ using typical design specifications.

We are told that $v_s(t) = 2 \cos(2\pi 60t) + n(t)$. The noise $n(t)$ is shown below.



- a) Determine the Fourier Transform of $n(t)$ for $n = \pm 1, \pm 2, \pm 3$ by integrating numerically. To generate the signal $n(t)$:
- Determine the period from the figure shown above
 - Use the sawtooth command in MATLAB. Check the Mathworks page on the sawtooth command to see an example on how to use the sawtooth command to create a triangle wave that looks like the one in the picture.
 - Make sure the triangle wave you create has the same phase as the signal shown in the figure above.

When integrating, I would recommend dividing the period into 10000 evenly space samples. You will need to determine the time step Δt . There is an example video on the Canvas page.

Determine the corresponding signals $C_n \cos(n\omega_o t + \phi_n)$ for $n = 1, 2, 3$.

You can verify your answers by integrating by hand, but it will be messy. If you really want to verify your answers, you can try to generate more harmonics and recreating the waveform using the harmonics.

- b) We now must design the filter. Let's assume we have the following specifications:
- The fundamental component of $n(t)$ must be reduced to about 1% of its input value. Use this spec to determine an approximate desired filter magnitude at the fundamental frequency of $n(t)$.

- The 60Hz component of $v_s(t)$ must not be significantly affected. This means that the amplitude of the output 60Hz component must be almost the same as the amplitude of the input component. The resulting phase shift should be less than 4 degrees.

You are given the following choices for the filters:

$$H_1(\omega) = \frac{1}{1 + j\frac{\omega}{\omega_c}}$$

$$H_2(\omega) = \frac{\omega_c^2}{(j\omega)^2 + j\frac{2}{\sqrt{2}}\omega_c\omega + \omega_c^2}$$

$$H_4(\omega) = \frac{\omega_c^4}{((j\omega)^2 + j0.7654\omega_c\omega + \omega_c^2)((j\omega)^2 + j1.8478\omega_c\omega + \omega_c^2)}$$

In each case, the frequency ω_c is a constant known as the corner frequency. This is the frequency at which the magnitude of the transfer function has fallen -3dB below its value at DC.

Select an appropriate filter to meet the requirements. To do so, you must choose ω_c for the various filters. All three of the filters can meet one of the requirements and only one can meet both.

Explain your filter choice in detail using appropriate bode plots.

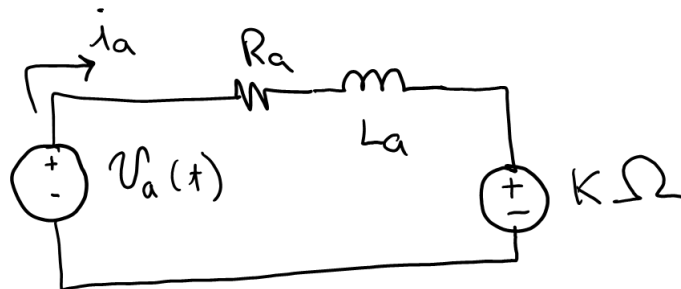
Determine the output signal for $v_{s,OUT}(t)$ for your filter choice. You should include the 60Hz term, and first, second, and third harmonics of $n(t)$.

A few hints:

- You should consider using the bode command in MATLAB. To use bode, you should go back to your learnings from 2112, where you learned that $s = j\omega$ and wrote $H(s)$.
- Watch the video on how to use the bode command in MATLAB.

Problem 2 – A PWM motor drive

In project 1, you were given the model for a DC motor. The circuit model for the DC motor is shown below:



The variable Ω is the speed of the motor in rad/sec. Note that the model includes a speed-dependent voltage source.

The mechanical component of the motor is represented by Newton's Second Law for rotation, which states:

$$(\text{Moment of Inertia}) \times (\text{Angular Acceleration}) = \text{Net Torque}$$

Mathematically, this is:

$$J \frac{d\Omega}{dt} = K i_a - \beta \Omega$$

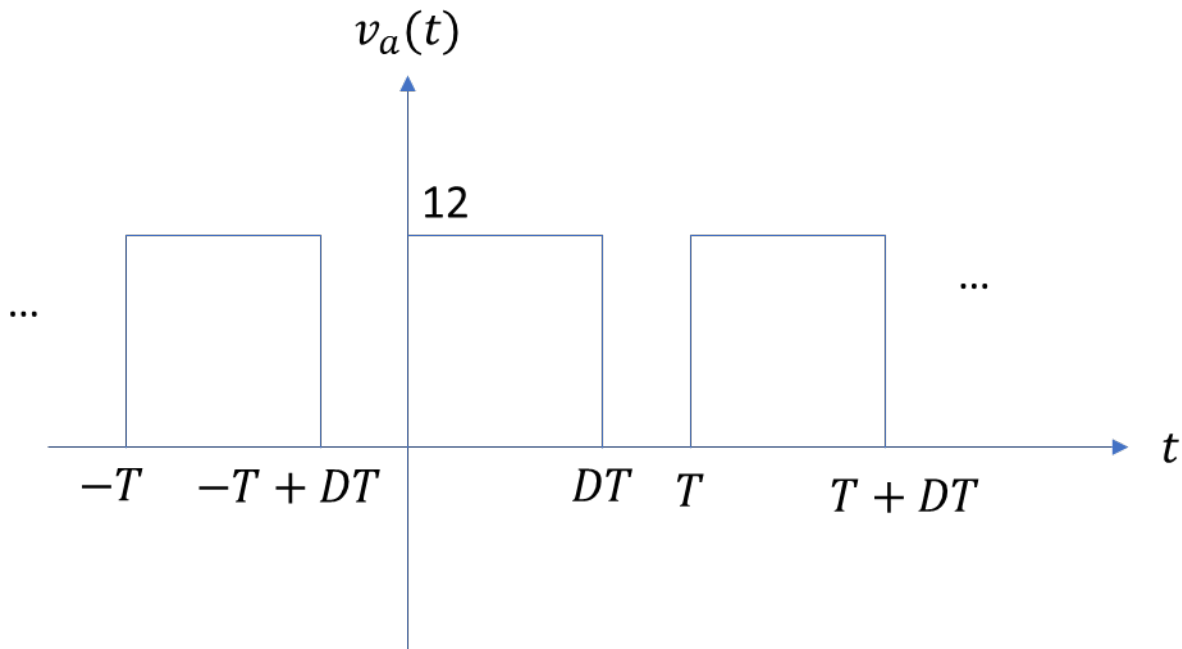
Where:

- β : Damping ratio
- J : Moment of inertia
- K : Motor constant

The motor you are controlling is has the following parameter values:

- $L = 0.01 \text{ H}$
- $R = 3.38 \text{ Ohms}$
- $K = 0.029 \text{ Vs/rad}$
- $J = 2 \times 10^{-4} \text{ kg m}^2$
- $\text{beta} = 0.5 \times 10^{-5} \text{ Nms/rad}$

In this case, the motor will be driven by a pulse width modulated (PWM) signal such as the one shown below:



This waveform is periodic with a period T , a peak value of 12, a minimum value of 0, and a duty ratio D . Please note that the duty ratio can vary but is a fraction between 0 and 1.

- Determine a differential equation for $i_a(t)$ from analyzing the electrical circuit.

- b) Using the two differential equations, create a transfer function that has $V_a(\omega)$ as its input and $\Omega(\omega)$ as its output.
- c) Plot the magnitude of the transfer function you created in part b. In this particular case, generate the plot without using the Bode command. To do so:
 - a. Use the logspace command to create 10,000 frequencies between 0.01 rad/sec and 10,000 rad/sec.
 - b. Generate a vector containing the elements of the complex function $H(\omega) = \Omega(\omega)/V_a(\omega)$.
 - c. Plot the magnitude of the transfer function versus the log of frequency using the semilogx command. The vector that you plot should be $20 \log_{10} |H(\omega)|$. Use the abs command in MATLAB to create the magnitude and use the log10 command.
- d) Use your plot from part c to do the following:
 - Determine a switching frequency $f = \frac{1}{T}$. Select a switching frequency so that the amplitude of the signal at the switching frequency will be about 1% of the DC value. Explain your choice for the switching frequency.
 - Determine the DC voltage that will be required to turn the motor at a speed of 324 rad/sec. **This value is determined by examining the transfer function when a DC input is applied. Think carefully about the frequency of a DC input.**
- e) Compute the DC term of the Fourier series for the PWM waveform as a function of D . Determine the value of D you need to apply the appropriate DC voltage to the motor that you determined in part d.
- f) To keep things simple, determine the complex Fourier series coefficients for a PWM waveform with $D = 0.5$. What is the amplitude C_1 of the cosine $C_1 \cos(\omega_0 t + \phi)$ at the fundamental frequency $\omega_0 = 2\pi/T$? Use this value to predict the amount of speed variation that will occur at the switching frequency. Note that the output of the filter is a speed variation of the form $\Omega(t) = C_1 \cos(\omega t + \phi)$. This means the speed is varying a little bit around a constant value.
- g) Using your work from Project 1, simulate the response of the motor when the voltage is a PWM waveform with the duty ratio D and the switching frequency you determined in part e. In this case, you should do the following:
 - Use the square command to create $v_a(t)$
 - Assume a time step small enough that you can see 10,000 points in one switching period T .
 - Run your simulation for 10 seconds

What is the average value of the speed in steady-state? Does it match your approximation well? It should match very closely (way less than 1% error).

What is the peak-to-peak value of the variation at the switching frequency? This value should be pretty close to your prediction, but the error will be a bit bigger. There are at least two reasons. Name them and explain.

- h) It is very easy to increase switching frequency with a microcontroller. Select a switching frequency such that the amplitude of the speed at the switching frequency is attenuated to

0.01% of the DC value. What is this switching frequency? Run a simulation and show that your result is approximately correct.