EE203 - Electrical Circuits Laboratory

Experiment - 2 Simulation
Time-Varying Signals

Objectives

1. Learn parameters that describe time-varying signals.
2. Become familiar with measurement of time-varying signal parameters.

Background

Time-Varying Signal Parameters

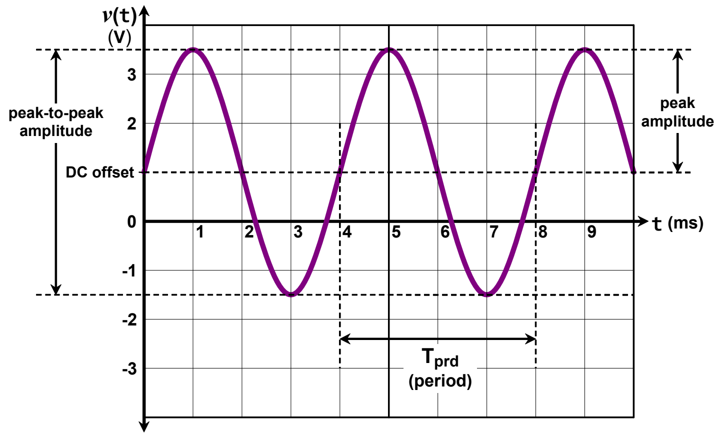
Almost all functional circuits process time-varying signals and generate time-varying outputs. **DC** (***direct current***) supplies and voltage or current regulators that generate constant outputs are the exceptions, however these circuits eventually support the operation of other functional circuits. In most applications, time-varying signals are also categorized as **AC** (***alternating current***) signals and they appear as **periodic** waveforms that are **repeated patterns** with a certain time duration or period. Periodic time-varying signals can be described by specifying a common waveform pattern, such as ***sinusoidal***, ***pulse*** (or ***square***), ***triangular*** (or ***saw-tooth***), with some amplitude and timing parameters explained in the following.

Peak-to-peak amplitude (V_{p-p})**:** Difference between the highest and lowest points of a waveform.

Peak amplitude (V_{peak})**:** Highest point of a waveform that has symmetric positive and negative amplitude variation around a reference level.

If a waveform has a non-zero reference, then an offset value should also be specified. For example, the sinusoidal signal shown below can be described with **2.5 V peak** amplitude and **+1 V** offset. This signal has **5 V peak-to-peak** variation between **–1.5 V** and **+3.5 V**.

Positive and negative peak amplitudes should be specified separately for asymmetric waveforms. Exceptionally, a single positive peak amplitude can be specified for waveforms that have **0 V** as the lower limit (i.e. some digital or pulsed signals).



Period and **frequency** of a waveform are essential timing parameters for all periodic waveforms.

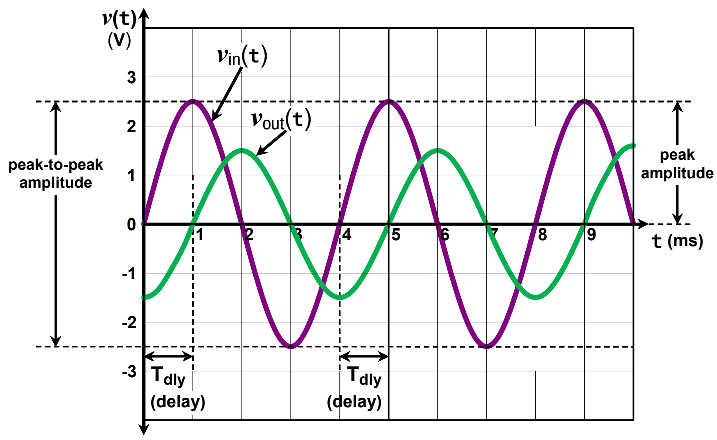
Period (T_{prd}): Time duration of repeated waveform pattern in seconds (**s**).
Frequency ($f = 1/T_{prd}$): Number of waveform patterns repeated in one second. The unit of frequency is **Hertz ($Hz = 1/s$)**.

In terms of these parameters, the mathematical expressions for the sinusoidal signal given above are

$$v(t) = 1\,V + 2.5\,V\,sin\left(2\pi\frac{t}{T_{prd}}\right)$$
$$= 1\,V + 2.5\,V\,sin(2\pi f\,t)$$
$$= 1\,V + 2.5\,V\,sin(\omega\,t)$$

where, $\omega = 2\pi f$ is the **angular frequency** in radians per second (**rad/s**). The multiplication with 2π is required to obtain the proper argument value for the ***sine*** function in radians. The argument ωt is equal 2π when $t = T_{prd}$ at the end of the first waveform period.

Another important parameter is the **time delay** or **phase** that specifies the shift in timing of periodic waveforms. In practice, the time delay or phase is measured relative to the time reference provided by another signal. In the following example, the output signal $v_{out}(t)$ is delayed by **1 ms** with respect to the input signal $v_{in}(t)$.



If the input signal $v_{in}(t)$ is taken as the reference with zero phase, then

$$v_{in}(t) = 2.5\,V\,sin(\omega\,t)$$
$$v_{out}(t) = 1.5\,V\,sin(\omega\,t - \theta)$$

where the timing parameters are

$$\mathbf{f} = \frac{1}{T_{prd}} = \frac{1}{4\ \mathrm{ms}} = 250\ \mathrm{Hz}, \qquad \omega = 2\pi f = 500\pi\ \mathrm{rad/s}$$

and the phase **θ** of $v_{out}(t)$ is given by $\mathbf{T_{dly}}$ between zero-cross points of the two waveforms:

$$\theta = 2\pi \frac{T_{dly}}{T_{prd}} = 2\pi \frac{1\ \mathrm{ms}}{4\ \mathrm{ms}} = \pi/2\ \mathrm{rad} = 90^{\circ}$$

The output signal $v_{out}(t)$ is described as having a **lagging** phase, since it appears later in time compared to the input $v_{in}(t)$. As a result of the negative phase shift **–θ**, the output $v_{out}(t)$ is **0 V** at **t = 1 ms**, whereas $v_{in}(t)$ has its peak value at this time instant. In the opposite case, where an output waveform is shifted left in the time axis, it has a **leading** phase relative to the reference signal.

Pulse Waveform Parameters

Pulse waveforms appear in a variety of shapes in common application areas, such as logic circuits, digital communications, and switching power control. Description of pulse waveforms require additional timing parameters:

On time (T_{on}) or high time (T_{high}): Time duration where the signal is at **active level** (mostly with a high amplitude) in a pulse waveform.

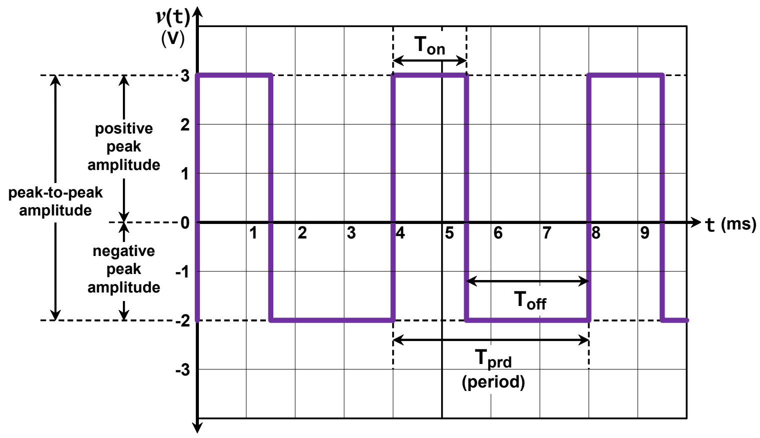
Off time (T_{off}) or low time (T_{low}): Time duration where the signal remains idle at reference level (mostly with a low amplitude) in a pulse waveform.

Duty cycle (DC): Ratio of on time to period of a pulse waveform. Duty cycle is usually expressed as a percentage:

$$\text{Duty cycle} = \frac{T_{on}}{T_{on} + T_{off}} \times 100\ \% = \frac{T_{on}}{T_{prd}} \times 100\ \%$$

As shown in the following example, if $\mathbf{T_{prd} = 4.0\ ms}$ and $\mathbf{T_{on} = 1.5\ ms}$ for a pulse waveform, then its duty cycle is

$$\text{Duty cycle} = \frac{1.5}{4.0} \times 100\ \% = 37.5\ \%.$$

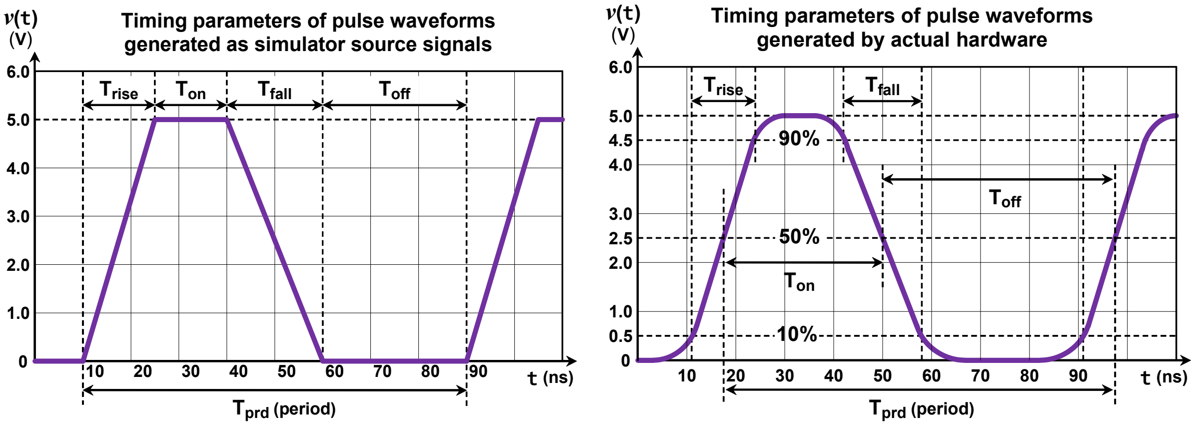


Transitions between high and low signal levels of a pulse waveform appear as sudden jumps when we observe low frequency signals. However, all signal changes occur in a finite time in actual circuits. Output of an ordinary CMOS digital circuit changes between high and low signal levels in **20 ns** (**= 0.02 μs**). It is not possible to see these transitions, when an oscilloscope displays a **250 Hz** waveform which has a period ($\mathbf{T_{prd}}$ **= 4 ms = 4000 μs**) **200,000** times longer than the transition time. If the frequency is increased to **2.5 MHz** (**= 2,500,000 Hz**), then the transitions can be observed as a function of time. Transition times of a pulse signal are specified as **rise time** and **fall time**.

Rise time (T_{rise}): Time it takes for a signal to increase from low level to high level in a pulse waveform.

Fall time (T_{fall}): Time it takes for a signal to decrease from high level to low level in a pulse waveform.

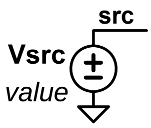
Simulation programs can generate ideal pulse waveforms with linear transitions (or ramp functions) between high and low signal levels. Timing parameters of the idealized source waveforms generated by LTspice are specified as shown on the left in the following figure. On the other hand, realistic pulse waveforms generated by actual hardware have non-linear transition functions. In practice, rise time and fall time of these waveforms are defined for the transitions between **10 %** and **90 %** of the low-to-high signal range. On time and off time are defined as the time between crossing points at **50 %** as shown on the right. These definitions are required for consistency of timing specifications and measurements on actual pulse waveforms.



Preliminary Work

1. Read the procedure given for this experiment, and make sure that you have the required knowledge about the laboratory equipment to perform the specified steps in case you need to make the measurements with real components and devices. Refer to **EELab_GuideBeginner.pdf** to refresh your memory. Read the section titled ***Grounding of Test Equipment***, regarding monitoring of differential voltages with an oscilloscope.

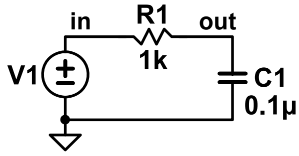
2 Open a new schematic file in LTspice and place a voltage source with a net label at its positive output as shown below.



Set the **Vsrc** parameters to obtain the following waveforms. Verify the voltage output by displaying the voltage at the **src** node after running a simulation.
a) 1 kHz sinusoidal signal with **10 V_{p-p}** amplitude and **0 V** DC offset
b) 1 kHz sinusoidal signal with **10 V_{p-p}** amplitude and **5 V** DC offset
c) 1 kHz pulse waveform that changes between **0 V** and **5 V** with **50%** duty cycle
d) 10 kHz pulse waveform that changes between **0 V** and **5 V** with **50%** duty cycle
e) 10 kHz pulse waveform that changes between **0 V** and **5 V** with **25%** duty cycle

Procedure

1.1 Build the circuit shown below on LTspice. Enter the **C1** capacitor value as **0.1u** (with the letter "**u**") or **100n**. The **C1** capacitor is necessary just to obtain different waveforms from a single voltage source. You will not make any calculations with **C1**.



1.2 Set the **V1** signal to **5 V** ***sin*(2*π* 1000 t)**. Right-click on the **V1** voltage source, click on the **Advanced** button and select the **SINE** option to obtain a **1 kHz** sinusoidal signal with **0 V** offset and **5 V** peak amplitude. The component value of **V1** should appear as "**SINE(0 5 1k)**" on the schematic. Place the net labels "**in**" and "**out**" as shown in the figure.

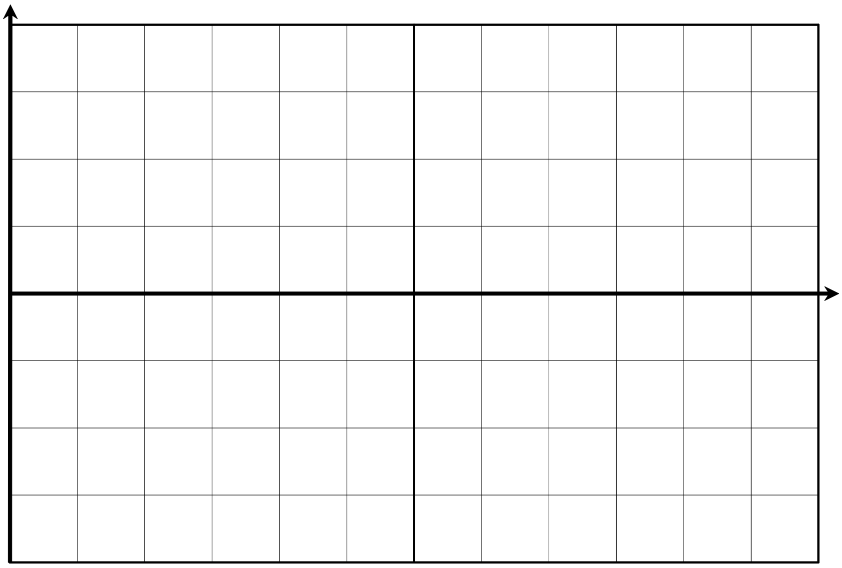
1.3 Enter the SPICE directive "**.tran 10m**" to set the simulation time to **10 ms**. Run the simulation with the **V1** frequency and **R1** settings listed in the following table. Measure the peak-to-peak amplitude of v_{out} and its time delay relative to v_{in}, and calculate v_{out} phase. Change the "**.tran 10m**" directive to observe **~30** waveform cycles at the other frequency settings. Make your measurements near the right end of the waveform window to avoid transient offset variations that appear at the beginning.

Hint: To make accurate measurements, zoom into a section of the waveform window by selecting a rectangular area with the mouse pointer. LTspice displays the amplitude and time difference corresponding to the rectangle borders as you hold down the mouse button.

V1 frequency (**kHz**)	**R1** (**kΩ**)	v_{out} amplitude (**Vp-p**)	v_{out} delay (**ms**)	v_{out} phase (**degree**)
1.0	**1.0**			
1.0	**3.3**			
1.0	**10.0**			
3.3	**1.0**			
3.3	**3.3**			
3.3	**10.0**			
10.0	**1.0**			
10.0	**3.3**			
10.0	**10.0**			

2.1 Change the **V1** source to obtain a **1 kHz** pulse waveform. Right-click on the **V1** voltage source, select the **PULSE** option, and enter the following parameters: Vinitial = **0**, Von = **5**, Tdelay = **0**, Trise = **1u**, Tfall = **1u**, Ton = **0.5m**, Tperiod = **1m**.

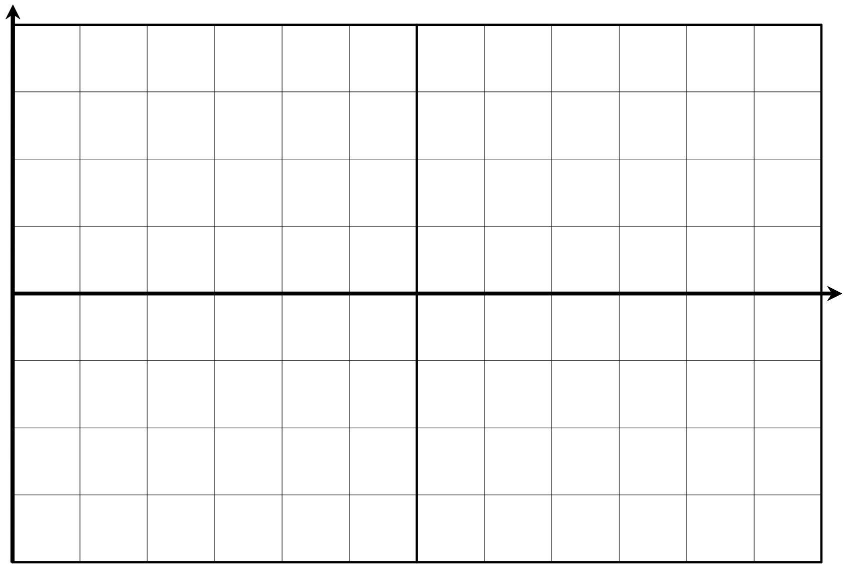
2.2 Set the simulation time to **3 ms**, and run simulation. Display the voltage across **R1** in addition to v_{in} and v_{out}. Right-click on the waveform window, select the **Add Traces** option, and enter the expression **V(in) – V(out)**. Draw two periods of the three waveforms, and record all voltage levels at the v_{in} transitions.



Measure the three voltages displayed on the waveform window at the time instants specified in the following table.

Time of measurement	v_{in} (V)	v_{out} (V)	$v_{in} - v_{out}$ (V)
right after v_{in} rising edge			
middle of v_{in} ON (**5V**) cycle			
right before v_{in} falling edge			
right after v_{in} falling edge			
middle of v_{in} OFF (**0V**) cycle			
right before v_{in} rising edge			

2.3 Repeat part **2.2** after changing pulse frequency to **10 kHz** (set the **V1** source parameters: Ton = **50u**, Tperiod = **100u**).



Measure the three voltages displayed on the waveform window at the time instants specified in the following table.

Time of measurement	v_{in} (**V**)	v_{out} (**V**)	$v_{in} - v_{out}$ (**V**)
right after v_{in} rising edge			
middle of v_{in} ON (**5V**) cycle			
right before v_{in} falling edge			
right after v_{in} falling edge			
middle of v_{in} OFF (**0V**) cycle			
right before v_{in} rising edge			

3.1 Zoom into the rising edge of the v_{in} waveform repeatedly until you can clearly identify the linear ramp from **0 V** to **5 V**. Measure the rise time from **0 V** to **5 V** and verify the **Trise** setting of the voltage source. Similarly, zoom into the falling edge of the v_{in} waveform and mesure the fall time.

T_{rise} = __________ **T_{fall} = __________**

3.2 Right-click on the value text "**PULSE(0 5 0 1u 1u 50u 100u)**" of **V1** source on the schematic and enter a new value given by "**PULSE(0 5 0 1n 1n 50u 100u)**". Run simulation and repeat the rise time and fall time measurements on the v_{in} waveform.

T_{rise} = __________ **T_{fall} = __________**

Questions

Q1. Describe the variations in v_{out} amplitude and phase as a function of **R1** when the v_{in} frequency is **10 kHz** in step-2 of the experiment. Predict the v_{out} amplitude and phase that will be obtained at **10 kHz** when **R1 is 100 kΩ**.

Q2. Describe the variations in v_{out} amplitude and phase as a function of v_{in} frequency when **R1** is **10 kΩ** in step-2 of the experiment. Predict the v_{out} amplitude and phase that will be obtained at **100 kHz** when **R1** is **10 kΩ**.

Q3. Compare the v_{out} amplitude and phase obtained in step-2 of the experiment for the couple of settings given below.

setting 1: v_{in} frequency **= 1 kHz**, **R1 = 10 kΩ**
setting 2: v_{in} frequency **= 10 kHz**, **R1 = 1 kΩ**

Are there any other couple of settings that produced similar results?

Q4. Verify that the voltage measurements recorded in step **2.2** and **2.3** are in accordance with the Kirchhoff's Voltage Law. Explain any discrepancies.

Q5. In a practical laboratory environment, **V1** voltage source will be a signal generator. What happens if you try to monitor the voltage across **R1** by using a single oscilloscope probe as shown below? Why?