Lab 8 - Introduction to AC Currents and Voltages

OBJECTIVES

• To understand the meanings of amplitude, frequency, phase, reactance, and impedance in AC circuits.

• To observe the behavior of resistors, capacitors, and inductors in AC circuits.

OVERVIEW

Until now, you have investigated electric circuits in which a battery provided an input voltage that was effectively constant in time. This is called a DC or Direct Current signal. [A steady voltage applied to a circuit eventually results in a steady current. Steady voltages are usually called DC voltages.]

Signals that change over time exist all around you and many of these signals change in a regular manner. For example, the electrical signals produced by your beating heart change continuously in time.
There is a special class of time-varying signals. These signals can be used to drive current in one direction in a circuit, then in the other direction, then back in the original direction, and so on. They are referred to as AC or Alternating Current signals.

It can be shown that any periodic signal can be represented as a sum of weighted sines and cosines (known as a Fourier series). It can also be shown that the response of a circuit containing resistors, capacitors, and inductors (an “RLC” circuit) to such a signal is simply the sum of the responses of the circuit to each sine and cosine term with the same weights.

We further note that a cosine is just a sine that is shifted in time by one-quarter cycle. So, to analyze an RLC circuit we need only find the response of the circuit to an input sine wave of arbitrary frequency.

Let us suppose that we have found a way to generate a current of the form:

\[ I(t) = I_{\text{max}} \sin(\omega t) \]  \hspace{1cm} (8.1)

\textbf{Note:} Here we use the \textit{angular frequency}, \( \omega \), which has units of radians per second. Most instruments report the \textit{frequency}, \( f \), which has units of cycles per second or Hertz (Hz). The frequency is the inverse of the period \( (f = 1/T) \). Clearly, \( \omega = 2\pi f \).

We can see from Ohm’s Law that the voltage across a resistor is then given:

\[ V_R(t) = I_{\text{max}} R \sin(\omega t) = V_{R,\text{max}} \sin(\omega t) \]  \hspace{1cm} (8.2)

Without proof\textsuperscript{1} we will state that the voltage across a capacitor is given by:

\[ V_C = q/C \quad \text{or} \quad \frac{dV_C}{dt} = I/C \quad \text{and} \quad V_L = L \frac{dI}{dt}. \]

\textsuperscript{1} You can verify these equations by plugging them into \( V_C = q/C \) (or \( dV_C/dt = I/C \)) and \( V_L = L \frac{dI}{dt} \).
and the voltage across an inductor is given by:

\[ V_L(t) = \omega L I_{\text{max}} \cos(\omega t) = V_{L,\text{max}} \sin(\omega t + \frac{\pi}{2}) \]  

(8.4)

Figure 8.1 shows a plot of the phase relationships between \( I \), \( V_R \), \( V_C \), and \( V_L \). We can see that the voltage across a resistor is in phase with the current; the voltage across an inductor leads the current by 90°; and the voltage across a capacitor lags the current by 90°.

We make the following definitions,

\[ X_C \equiv \frac{1}{\omega C} \quad \text{and} \quad X_L \equiv \omega L \]

\( X_C \) is called the reactance of the capacitor and \( X_L \) is the reactance of the inductor. Capacitors and inductors behave like frequency dependent resistances, but with the additional effect of causing a ±90° phase shift between the current and the voltage.

Arbitrary combinations of resistors, capacitors and inductors will also have voltage responses of this form (a generalized Ohm’s Law):

\[ V = I_{\text{max}} Z \sin(\omega t + \varphi) \]  

(8.5)

\( Z \) is called the impedance (and has units of resistance, Ohms) and \( \varphi \) is called the phase shift (and has units of angle, degrees or radians). The maximum voltage will be given by:

\[ V_{\text{max}} = I_{\text{max}} Z \]  

(8.6)

For a capacitor, \( Z = X_C = 1/\omega C \) and \( \varphi = -90^\circ \) while for an inductor, \( Z = X_L = \omega L \) and \( \varphi = +90^\circ \).

Figure 8.2 shows the relationship between \( V \) and \( I \) for an example phase shift of +20°. We say that \( V \) leads \( I \) in the sense that the voltage rises through zero a time \( \Delta t \) before the current. When the voltage rises through zero after the current, we say that it lags the current.
Note: The relationship between $\varphi$ and $\Delta t$ is given by

$$\varphi = 2\pi \left( \frac{\Delta t}{T} \right) = 360^\circ \times f \Delta t$$

where $T$ is the period and $f$ is the frequency.

In Investigation 1, you will explore how a time-varying signal affects a circuit with just resistors. In Investigations 2 and 3, you will explore how capacitors and inductors influence the current and voltage in various parts in an AC circuit.

**NOTE:** In this lab you will be performing a lot of similar calculations. You might find it extremely beneficial to use an Excel spreadsheet Lab8-Table 1-1.xls with all formulae provided to you. The file will help you calculate the values in Tables 8.1, 8.2, and 8.3. You are expected to understand how the values in the spreadsheet are produced and your TAs might ask you to reproduce some of the calculations manually.

**INVESTIGATION 1: AC SIGNALS WITH RESISTORS**

In this investigation, you will consider the behavior of resistors in a circuit driven by AC signals of various frequencies.

You will need the following materials:

- three voltage probes
- 500 $\Omega$ “reference” resistor
- 1 k$\Omega$ “device under test” resistor
- multimeter
- test leads
- external signal generator
Activity 1-1: Resistors and Time-Varying (AC) Signals.

Consider the circuit in Figure 8.3. This configuration is known as a voltage divider and is a very commonly used circuit element. When implemented with resistors, it is used to attenuate signals (mechanical volume controls for stereos are usually adjustable voltage dividers). As we’ll see later, when implemented with capacitors and/or inductors, the resulting frequency dependent attenuator can be used to separate high frequencies from low ones. Such circuits are called filters.

Resistor $R_0$ is our “reference” resistor (and how we’ll measure the current) and $R$ is our “device under test” (or DUT, if you like TLA).²

We seek to find the relationship between the driving voltage $V$, and the voltage across our “device under test”, $V_R$. To do so we use Kirchoff’s Circuit Rules and Ohm’s Law.

First, we see from the Junction Rule that the current must be the same in both resistors. Second, from the Loop Rule we see that the sum of the emf’s and voltage drops must be zero. Hence:

$$V = V_0 + V_R$$

Then using Ohm’s Law we get:

$$V = IR_0 + IR = I(R_0 + R)$$

Plugging in our standard forms for the current and voltage [Equations (8.1) and (8.5)], we get

$$V_{\text{max}} \sin(\omega t + \varphi) = I_{\text{max}}(R_0 + R) \sin(\omega t)$$

Recall the trigonometric identity:

$$\sin(\alpha + \beta) = \sin(\alpha) \cos(\beta) + \cos(\alpha) \sin(\beta) \quad (8.8)$$

² A TLA is a “Three Letter Acronym”, and they are all too common in technical jargon.
Hence:

\[ V_{\text{max}} \left( \sin(\omega t) \cos(\varphi) + \cos(\omega t) \sin(\varphi) \right) = I_{\text{max}} (R_0 + R) \sin(\omega t) \]

Equating the coefficients of \( \sin(\omega t) \) and \( \cos(\omega t) \) yields

\[ V_{\text{max}} \cos(\varphi) = I_{\text{max}} (R_0 + R) \]

and

\[ V_{\text{max}} \sin(\varphi) = 0 \]

Since \( \sin(\varphi) = 0 \) and \( \cos(\varphi) \) is positive, there is no phase shift:

\[ \varphi = 0 \quad (8.9) \]

The magnitude of the current is given by:

\[ I_{\text{max}} = \frac{V_{\text{max}}}{R_0 + R} \quad (8.10) \]

Hence, the impedance of this series combination of two resistors is given by:

\[ Z_{RR} = \frac{V_{\text{max}}}{I_{\text{max}}} = R_0 + R \quad (8.11) \]

We can now calculate the magnitude of the voltage across \( R \):

\[ V_{R,\text{max}} = I_{\text{max}} R = V_{\text{max}} \frac{R}{Z_{RR}} \quad (8.12) \]

Similarly,

\[ V_{0,\text{max}} = I_{\text{max}} R_0 = V_{\text{max}} \frac{R_0}{Z_{RR}} = V_{\text{max}} \left( \frac{R_0}{R_0 + R} \right) \quad (8.13) \]

1. Measure the resistors:
   - \( R_0: \) \( \Omega \)
   - \( R: \) \( \Omega \)

2. Connect the circuit in Figure 8.3.

**Note:** Use the red connector (“Lo Ω”) on the power supply for the positive (“+”) side and the black connector for the negative terminal.

**Question 1-1:** Assume that \( V \) is a sinusoid of amplitude (peak voltage) \( V_{\text{max}} = 4V \). Use Equations (8.12) and (8.9) to predict \( Z_{RR}, V_{R,\text{max}} \) and \( \varphi \) for driving frequencies of 50 Hz, 200 Hz, and 800 Hz. Show your work.

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3 The subscript “RR” simply serves to remind us that this \( Z \) for two resistors in series.
\[ f = 50 \text{ Hz} \quad Z_{RR} = \underline{\ \ \ \ \ \ \ }, \quad V_{R,max} = \underline{\ \ \ \ \ \ }, \quad \varphi = \underline{\ \ \ \ \ \ } \]

\[ f = 200 \text{ Hz} \quad Z_{RR} = \underline{\ \ \ \ \ \ \ }, \quad V_{R,max} = \underline{\ \ \ \ \ \ }, \quad \varphi = \underline{\ \ \ \ \ \ } \]

\[ f = 800 \text{ Hz} \quad Z_{RR} = \underline{\ \ \ \ \ \ \ }, \quad V_{R,max} = \underline{\ \ \ \ \ \ }, \quad \varphi = \underline{\ \ \ \ \ \ } \]

**Question 1-2:** On the axes below, sketch your *quantitative* predictions for \( V, V_0 \) and \( V_R \), versus time, \( t \). Assume that \( V \) is a 200 Hz sinusoid of amplitude (peak voltage) 4 V. Draw at least one full cycle. Show your work below.

3. Turn on the signal generator (the switch is on the back). Set the frequency to 200 Hz, the amplitude to about half scale, and select a sinusoidal waveform (the other options are “triangle” and “square” waves).

4. Open the experiment file called **L08A1-1 AC Voltage Divider**. You will see an oscilloscope display. An oscilloscope is a device that shows voltages versus time. Each voltage waveform is called a trace and you should see three traces on the screen (VP\textsubscript{A}, VP\textsubscript{B}, and VP\textsubscript{C}).

5. Take a little to play with the controls. Click **Start**. Then click on the little black arrows for the time and voltage scales. See how they change the display.

6. Play with the “trigger level” (the little arrow on the left-hand-side) a bit to see how it operates. The trigger determines when oscilloscope starts its sweep by looking at a specific input and determining when it either rises above or falls below a specified level. You can select the “trigger source” by clicking on the appropriate box on the right-hand-side of the scope display. You can “click-and-drag” the trigger level with the mouse. Note: The trigger level indicator will be the same color as trigger source trace.

7. Double-click on the display to bring up the settings window. Here you can select the trigger source, set the trigger level, and the direction that the signal must be passing the trigger level to start the scope.
8. Verify that the signal generator is set to 200 Hz and adjust the amplitude until $V_{\text{max}} (V_{\text{PC}})$ is 4 V. Set the oscilloscope such that the time axis is set to one millisecond per division and that all three voltage scales are set to one volt per division. [Note that the frequency knob is “speed sensitive” in that the faster you spin the dial, the more it changes the frequency per unit angle.]

9. When you have a good display, click **stop**.

10. Use the **Smart Tool** to find the maxima for $V$, $V_0$, and $V_R$. Also measure the time delay ($\Delta t$) between $V$ and $V_0$. Enter these data into the middle column of Table 8.1. Note that you’ll get more precise time measurements if you look at where the traces “cross zero”.

    **Caution:** When using the **Smart Tool**, make sure that it is “looking” at the correct trace. The digits will be the same color as the trace.

11. Vary the frequency between about 20 Hz and 1,000 Hz.

    **Question 1-3:** Describe your observations, with particular attention paid to the amplitudes and relative phases.

12. Now make the same measurements for 50 Hz and 800 Hz and enter the data into Table 8.1.

13. Calculate $I_{\text{max}} = V_{0,\text{max}}/R_0$ and $Z_{RR} = V_{\text{max}}/I_{\text{max}}$ for each of frequency. Also calculate the phase shifts (in degrees) between $V$ and $V_0$. Enter the results into Table 8.1. Note the phase shifts between $V$ and $V_R$, and, between $V_0$ and $V_R$.

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Table 8.1:
**Question 1-4:** Discuss the agreement between your experimental results (see Question 1-3 and Table 8.1) and your predictions. Specifically consider the frequency dependencies (if any).

**Note:** Do not disconnect this circuit as you will be using a very similar one in Investigations 2 and 3.

### INVESTIGATION 2: AC SIGNALS WITH CAPACITORS

In this investigation, you will consider the behavior of capacitors in a circuit driven by AC signals of various frequencies.

You will need the following materials:

- three voltage probes
- 500 Ω “reference” resistor
- 470 nF “device under test” capacitor
- multimeter
- test leads
- signal generator

**Activity 2-1: Capacitors and Time-Varying (AC) Signals.**

Consider the circuit in Figure 8.4. Resistor $R_0$ is again our “reference” resistor. C is our “device under test”.

Now we seek to find the relationship between the driving voltage, $V$, and the current in the circuit. From Kirchhoff’s Rules and Equations (8.2) and (8.3) we get:
\[ V_{\text{max}} \sin(\omega t + \varphi) = I_{\text{max}} R_0 \sin(\omega t) - I_{\text{max}} X_C \cos(\omega t) \]

Once again using the trigonometric identity and equating the coefficients of \( \sin(\omega t) \) and \( \cos(\omega t) \), we get

\[ V_{\text{max}} \cos(\varphi) = I_{\text{max}} R_0 \]

and

\[ V_{\text{max}} \sin(\varphi) = -I_{\text{max}} X_C \]

Hence the phase shift is given by

\[ \tan(\varphi) = -\frac{X_C}{R_0} \quad (8.14) \]

The magnitude of the current is given by:

\[ I_{\text{max}}^2 = \frac{V_{\text{max}}^2}{R_0^2 + X_C^2} \quad (8.15) \]

Hence, the impedance of this series combination of a resistor and a capacitor is given by:

\[ Z_{RC} = \frac{V_{\text{max}}}{I_{\text{max}}} = \sqrt{R_0^2 + X_C^2} \quad (8.16) \]

We can now calculate the magnitude of the voltage across \( C \):

\[ V_{C,\text{max}} = I_{\text{max}} X_C = V_{\text{max}} \frac{X_C}{Z_{RC}} \quad (8.17) \]

Similarly,

\[ V_{0,\text{max}} = I_{\text{max}} R_0 = V_{\text{max}} \frac{R_0}{Z_{RC}} \quad (8.18) \]

14. Measure C:

C: ______________

15. Connect the circuit in Figure 8.4.

**Question 2-1:** Assume that \( V \) is a sinusoid of amplitude (peak voltage) \( V_{\text{max}} = 4V \). Use Equations (8.17) and (8.14) to predict \( Z, V_{C,\text{max}} \) and \( \varphi \) for driving frequencies of 50 Hz, 200 Hz, and 800 Hz. Show your work. [Hint: Don’t forget that \( X_C = 1/\omega C = 1/2\pi f C \)!

\[
\begin{align*}
\text{\( f = 50 \text{ Hz} \)} & \quad Z_{RC} = \hspace{1cm} V_{C,\text{max}} = \hspace{1cm} \varphi = \\
\text{\( f = 200 \text{ Hz} \)} & \quad Z_{RC} = \hspace{1cm} V_{C,\text{max}} = \hspace{1cm} \varphi = \\
\text{\( f = 800 \text{ Hz} \)} & \quad Z_{RC} = \hspace{1cm} V_{C,\text{max}} = \hspace{1cm} \varphi = \\
\end{align*}
\]
**Question 2-2:** On the axes below, sketch your *quantitative* predictions for \( V \), \( V_0 \) and \( V_C \) versus time, \( t \). Assume that \( V \) is a 200 Hz sinusoid of amplitude (*peak voltage*) 4 V. Draw at least one full cycle. Show your work below.

16. Continue to use **L08A1-1 AC Voltage Divider**.

17. Verify that the signal generator is set to 200 Hz and adjust the amplitude until \( V_{\text{max}} \) (\( V_{\text{P}_{\text{C}}} \)) is 4 V. Set the oscilloscope such that the time axis is set to one millisecond per division and that all three voltage scales are set to one volt per division.

18. Click **Start**. Trigger on \( V_0 \) (as it is proportional to the current). When you have a good display, click **stop**.

19. Use the **Smart Tool** to find the maxima for \( V \), \( V_0 \), and \( V_C \). Also measure the time delay \( (\Delta t) \) between \( V \) and \( V_0 \). Enter these data into the *middle* column of Table 8.2.

20. Vary the frequency between about 20 Hz and 1,000 Hz.

**Question 2-3:** Describe your observations, with particular attention paid to the amplitudes and relative phases.

21. Now make the same measurements for 50 Hz and 800 Hz and enter the data into Table 8.2.

22. Calculate \( I_{\text{max}} = \frac{V_{0,\text{max}}}{R_0} \) and \( Z_{RC} = \frac{V_{\text{max}}}{I_{\text{max}}} \) for each frequency. Also calculate the phase shifts (in degrees) between \( V \) and \( V_0 \). Enter the results into Table 8.2.
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Table 8.2:

**Question 2-4:** Discuss the agreement between your experimental results (see Question 2-3 and Table 8.2) and your predictions. Specifically consider the frequency dependencies (if any).

**INVESTIGATION 3: AC SIGNALS WITH INDUCTORS**

In this investigation, you will consider the behavior of inductors in a circuit driven by AC signals of various frequencies.

You will need the following materials:

- three voltage probes
- 500 $\Omega$ “reference” resistor
- 800 mH “device under test” inductor
- multimeter
- test leads
- signal generator

**Activity 3-1: Inductors and Time-Varying (AC) Signals.**

Consider the circuit in Figure 8.5. Resistor $R_0$ is again our “reference” resistor. L is our “device under test”.

Now we seek to find the relationship between the driving voltage, $V$, and the current in the circuit.

From Kirchoff’s Rules and Equations (8.2) and (8.4) we see:

$$V_{\text{max}} \sin(\omega t + \varphi) = I_{\text{max}}(R_0 + R_L) \sin(\omega t) + I_{\text{max}}X_L \cos(\omega t)$$

[Remember that $X_L = \omega L$ and our inductor has non-negligible resistance $R_L$.]

Using the identity and equating the coefficients of $\sin(\omega t)$ and $\cos(\omega t)$, we get
Figure 8.5:

\[ V_{\text{max}} \cos(\varphi) = I_{\text{max}}(R_0 + R_L) \]

and

\[ V_{\text{max}} \sin(\varphi) = I_{\text{max}}X_L \]

Hence the phase shift is given by:

\[ \tan(\varphi) = \frac{X_L}{(R_0 + R_L)} \] (8.19)

The magnitude of the current is given by:

\[ I_{\text{max}}^2 = V_{\text{max}}^2 \left( \frac{(R_0 + R_L)^2 + X_L^2}{(R_0 + R_L)^2} \right) \] (8.20)

Hence, the impedance of this series combination of a resistor and an inductor is given by:

\[ Z_{RL} = \frac{V_{\text{max}}}{I_{\text{max}}} = \frac{\sqrt{(R_0 + R_L)^2 + X_L^2}}{R_0 + R_L} \] (8.21)

We can now calculate the magnitude of the voltage across L:

\[ V_{L,max} = I_{\text{max}}X_L = V_{\text{max}} \frac{X_L}{Z_{RL}} = V_{\text{max}} \left( \frac{X_L}{\sqrt{(R_0 + X_L^2)}} \right) \] (8.22)

Similarly,

\[ V_{0,max} = I_{\text{max}}R_0 = V_{\text{max}} \frac{R_0}{Z_{RL}} = V_{\text{max}} \left( \frac{R_0}{\sqrt{(R_0 + R_L)^2 + X_L^2}} \right) \] (8.23)

23. Measure \( L \) and \( R_L \):

\( L: \) ___________ mH \hspace{1cm} \( R_L: \) ___________ \( \Omega \)
24. Connect the circuit in Figure 8.5.

**Question 3-1:** Assume that $V$ is a sinusoid of amplitude (peak voltage) $V_{\text{max}} = 4V$. Use Equations (8.22) and (8.19) to predict $Z_{RL}$, $V_{L,max}$ and $\phi$ for driving frequencies of 50 Hz, 200 Hz, and 800 Hz. Show your work.

\[
f = 50 \text{ Hz} \quad Z_{RL} = \quad V_{L,max} = \quad \phi = \\
f = 200 \text{ Hz} \quad Z_{RL} = \quad V_{L,max} = \quad \phi = \\
f = 800 \text{ Hz} \quad Z_{RL} = \quad V_{L,max} = \quad \phi = \\
\]

**Question 3-2:** On the axes below, sketch your quantitative predictions for $V$, $V_0$ and $V_L$ versus time, $t$. Assume that $V$ is a 200 Hz sinusoid of amplitude (peak voltage) 4 V. Draw two periods and don’t forget to label your axes. Show your work below.

25. Continue to use L08A1-1 AC Voltage Divider.

26. Verify that the signal generator is set to 200 Hz and adjust the amplitude until $V_{\text{max}} (V_{P_C})$ is 4 V. Set the oscilloscope such that the time axis is set to one millisecond per division and that all three voltage scales are set to one volt per division.

27. Click Start. When you have a good display, click stop.

28. Use the Smart Tool to find the maxima for $V$, $V_0$, and $V_L$. Also measure the time delays ($\Delta t$'s) between $V$ and $V_0$. Enter these data into the middle column of Table 8.3.
29. Vary the frequency between about 20 Hz and 1,000 Hz.

**Question 3-3:** Describe your observations, with particular attention paid to the amplitudes and relative phases.

30. Now make the same measurements for 50 Hz and 800 Hz and enter the data into Table 8.3.

31. Calculate $I_{\text{max}} = V_{0,\text{max}}/R_0$ and $Z_{RL} = V_{\text{max}}/I_{\text{max}}$ for each frequency. Also calculate the phase shifts (in degrees). Enter the results into Table 8.3.

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Table 8.3:

**Question 3-4:** Discuss the agreement between your experimental results (see Question 3-3 and Table 8.3) and your predictions. Specifically consider the frequency dependencies (if any).

**WRAP-UP**

**Question 3-5:** Do your results for all three circuits make intuitive sense for low frequencies? Explain. Answer this by considering switched DC circuits in the steady state (i.e., after things settle down). [A DC current (or voltage) can be thought of as the limit of a cosine as the frequency goes to zero.]
Question 3-6: Do your results for all three circuits make intuitive sense for high frequencies? Explain. Answer this by considering switched DC circuits immediately after the switch is closed or opened.

Please clean up your lab area