UNIVERSITY OF CALIFORNIA, DAVIS
Department of Electrical and Computer Engineering

Analog Circuits - Laboratory Instrumentation and Measurement Techniques

Written by: Charles Eldering; revised by: Richard Spencer

1. - Introduction

In order to obtain accurate measurements in the laboratory, a thorough understanding of the instruments used is required. For this reason it is necessary to review the basic laboratory instruments: the multimeter (a voltmeter, ammeter and ohmmeter combined in one instrument), the signal (or function) generator, power supplies, and the oscilloscope. The oscilloscope primer entitled "The XYZ's of Using a Scope" will provide sufficient background for the use of the oscilloscope and will be a useful reference. The purpose of this handout is to provide basic information concerning the use of multimeters, power supplies and function generators and to discuss the measurement of impedance using several techniques.

2. - Power Supplies

The power supplies commonly encountered in the laboratory are variable voltage supplies. It is important to note that on these power supplies **all output terminals are isolated from ground**. This means that although a voltage difference will appear between the output and common terminals, the common terminal is not connected to ground internally. For most applications, a connection between the common terminal and the ground terminal is necessary. Since the function generators and oscilloscopes are referenced to ground, once the common terminal of the power supply is grounded, all of the equipment will have a common reference.

3. - Function Generators

Function generators are capable of generating a number of waveforms and are used as an AC signal source. The output impedance of most of the function generators in your lab is 50 ohms. The outputs of the function generators are DC coupled and the maximum instantaneous AC plus DC voltages which can be generated are ±10 volts.

4. - Digital Multimeters (DMM)

The digital multimeter is an instrument capable of measuring AC and DC voltage and current as well as resistance. Assuming that the multimeter is an ideal instrument means that it will not disturb the circuit in any way while making a measurement. While the assumption that the meter will not disturb the circuit is generally valid, it is important to understand when the meter is disturbing the circuit and how it will affect the measurement.

4.1 - Resistance Measurements

For resistance measurements, the DMM is connected to the unknown resistance. The meter then either forces a small current through the component and measures the resulting voltage, or places a small voltage across the component and measures the resulting current. Since most multimeters are basically analog-to-digital converters set up to measure voltage, the most common method is to force a small current and measure the resulting voltage, the display is calibrated to indicate the corresponding resistance. When measuring resistances it is important to remember that any other current paths in parallel with the unknown resistances will affect the measurement. For this reason, it is important to remember to disconnect the component from the circuit when making the measurement. Also, note that if the impedance is complex (consisting of a real and an imaginary part), the DMM can only measure the real portion and it may not even be able to do that (e.g., what happens if you try and measure the "resistance" of a cap by forcing I and measuring V?). Other techniques must be used to determine the real and imaginary parts of the impedance.

4.2 - Voltage Measurements

Note the **ideal voltmeter** has **infinite input resistance**. This implies that when placed between two nodes in a circuit the ideal voltmeter measures the voltage between the nodes without drawing any current. The ideal voltmeter does not exist and all voltmeters have some input resistance. For digital voltmeters this resistance is in the range of 1M-50M ohms. Because of this high resistance, the voltmeter does not usually affect the circuit, although it is important to remember that there are situations in which the voltmeter may give readings which are inaccurate due to its loading of the circuit. Figure 1 shows the difference between a real and an ideal voltmeter.

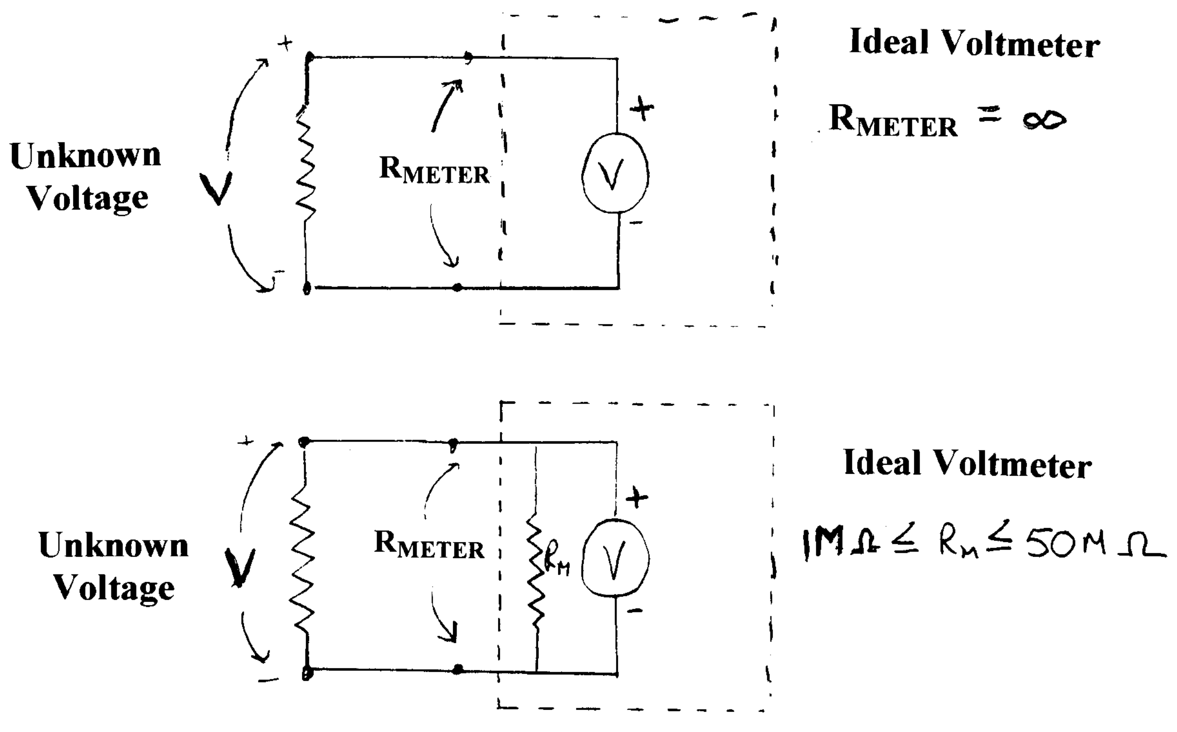

Figure 1

4.3 - Current Measurements

The **ideal ammeter** has **zero resistance**. By connecting it in series in a particular branch of a circuit, it is possible to measure the current in that branch. Real ammeters have some small resistance which normally does not affect the current measurement. Figure 2 illustrates ideal and real ammeters and shows their use in measuring currents in a circuit. Note that a circuit **must** be broken in order to insert an ammeter.

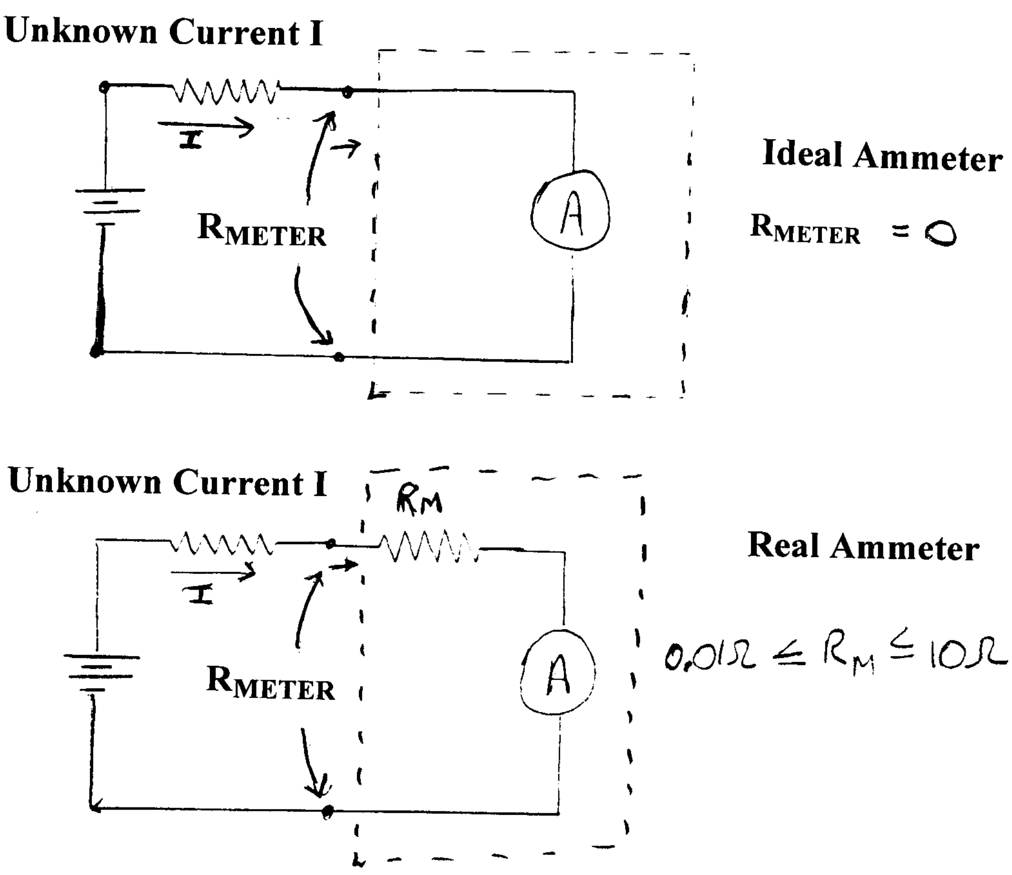

Figure 2

4.4 - AC Measurements

In making AC measurements one is faced with the problem of determining a value for a voltage or current which by nature is changing in value; an example of this would be the 60 Hz line voltage which is approximately 163 volts peak-to-peak. The most common method for describing AC voltages or currents is to use the *effective* or *root-mean-square* value. For current, the effective value of the current is equal to the value of the direct current which would deliver the same power to a given resistor as the AC current does. The value of the effective or rms current is given by

$$i_{eff} = \sqrt{\frac{1}{T}\int_0^T i^2 dt}$$

Effective or rms values of voltage can be defined similarly. For sinusoidal waveforms, the expression for effective current or voltage shows that the effective voltage is equal to the peak value of the voltage or current divided by $\sqrt{2}$. Thus, the household line voltage which is 163 volts peak-to-peak has an rms value of 120 volts. For other waveforms, the factor will be different and needs to be evaluated for each individual case.

The DMM can be used to make measurements of rms voltages or currents. In doing so, it is important to note that most **DMMs will yield accurate rms measurements only for certain waveforms over a limited frequency range**. The inaccuracy is due to the fact that these meters are usually measuring the average value instead of the RMS value, and then simply scale the result. This method works fine for sine-waves (for which the scale factor is set), but will be in error for waveforms with a different ratio of RMS to average values.

One meter you may encounter in the lab is the Fluke 8010A which is capable of making RMS measurements on sine waves, square waves (but only those which have both negative and positive going portions) and triangle/sawtooth waveforms. The accuracy is $\pm$0.5% up to 10 kHz. While this meter is quite accurate for a number of waveforms, it is sometimes advisable to use the oscilloscope for waveforms which are not purely sinusoidal.

5. - Matching and Impedance Measurements

We are very often concerned with knowing the input or output impedance of a given circuit. One reason for this is that in order to get power out of a given circuit efficiently, we want the load impedance to be the conjugate of the output impedance of the circuit. Figure 3 illustrates a simple example, with an output impedance R_{out} and a load impedance R_{load}. The maximum power transfer theorem for this case can be proven by writing the expression for the power dissipated in the load resistor as a function of the output resistance and finding the maximum. The result is simply that **power transfer is maximized when $R_{load} = R_{out}$.**

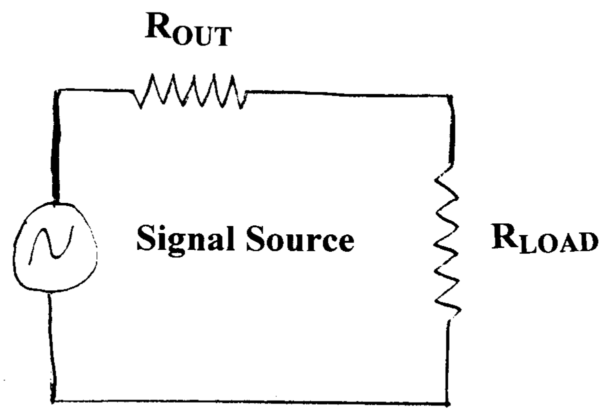

Figure 3

5.1 - Matching

A more common problem of matching which you will encounter in the laboratory is the matching of output impedances of equipment with cable impedances and termination impedances. A simple rule to remember is that in order to obtain proper matching, **all impedances, cable, input, output, and termination should be identical.** If the impedances are not equal, maximum power transfer will not take place and the reflected power may cause ringing in the signal. The oscilloscope primer contains several good examples of matching and illustrates the results when the oscilloscope impedances are mismatched to probe impedances.

In the laboratory , several different cable types are commonly encountered. They are:

Cable	Impedance	Connector
RG58	50 ohms	BNC
RG59	75 ohms	BNC

While the RG58 and RG59 cables have BNC connectors which are almost identical in appearance, it is important to note that they are not compatible and should not be used interchangeably. Most cable in the laboratory is RG58, but caution should be exercised to avoid destroying connectors by interchanging cables. The center conductor on a 75Ω BNC male connector is larger than on a 50Ω connector. Therefore, plugging a 75Ω male connector into a 50Ω female can damage the 50Ω connector. Also, a 50Ω male connector may not make reliable contact in a 75Ω female connector.

5.2 - Impedance Measurements

It should be clear that knowledge of input and output impedances is critical. However, for most active circuits it is not possible to simply connect an ohmmeter to the circuit to measure the impedance. The reason for this is that we are usually interested in an AC measurement and there is usually a DC bias on the circuit. Simply hooking a multimeter between the input and ground and forcing a small DC voltage on the input will clearly not bias the circuit properly. Therefore, it is necessary to use other techniques to measure input/output impedances.

5.2.1 - Direct Measurement of Voltage and Current

If the AC voltage at the input of a circuit and the AC current flowing into the circuit can be measured, it is clear that it will be possible to calculate the impedance of the circuit using ohms law. Figure 4 illustrates a method for determining the input voltage and current to a circuit. By placing a small resistance (e.g. 50 ohms) in series with the input signal, it is possible to determine the input current to the circuit; the voltage drop across the resistor can be measured on the oscilloscope or with a DMM. The voltage at the input can also be measured and the magnitude of the input impedance will be given by the ratio of the voltage to the current. Note that only the magnitude of the current is available if a DMM is used to make the measurement. If an oscilloscope is used, magnitude and phase information can be obtained. This method is illustrated in Figure 4. It is important to note that AC as well as DC measurements can be made. It is not necessary to use RMS values as long as both the current and voltage measurements are the same (e.g. peak-to-peak). The main problem with this measurement technique is that when the input currents are small (μA), the voltage drop across the measurement resistor will be very small and it will be difficult to obtain an accurate input current measurement.

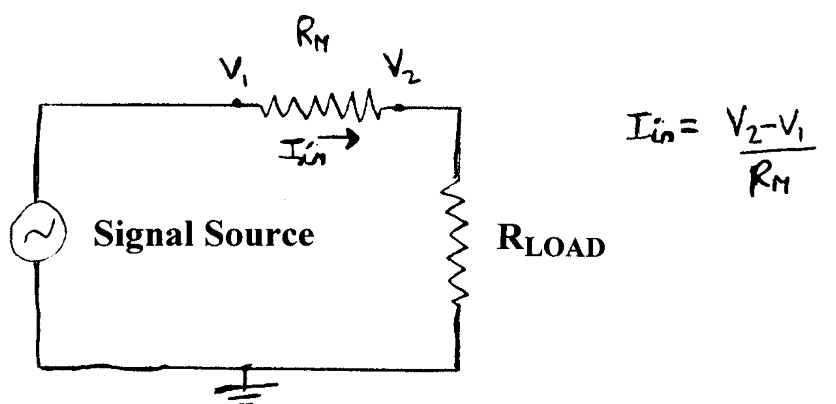

Figure 4

Figure 4. Note: Voltages V_1 and V_2 are measured with respect to ground.

5.2.2 - Voltage Divider Technique

For a voltage divider composed of two resistors, R_1 and R_2, the output voltage (the voltage across R_2 as shown in Figure 5a) will be equal to half of the input voltage when $R_1 = R_2$. Using this fact, it is possible to determine the input impedance of a circuit by replacing R_2 with the circuit and using a variable resistor as R_1, as shown in Figure 5b. By applying a signal source of known amplitude to the voltage divider and monitoring the voltage at the circuit input, the variable resistor can be adjusted until the voltage appearing at the circuit input is equal to one half of the input voltage. If a decade box is used as the variable resistor, the circuit impedance (magnitude only) can be read directly from the decade box.

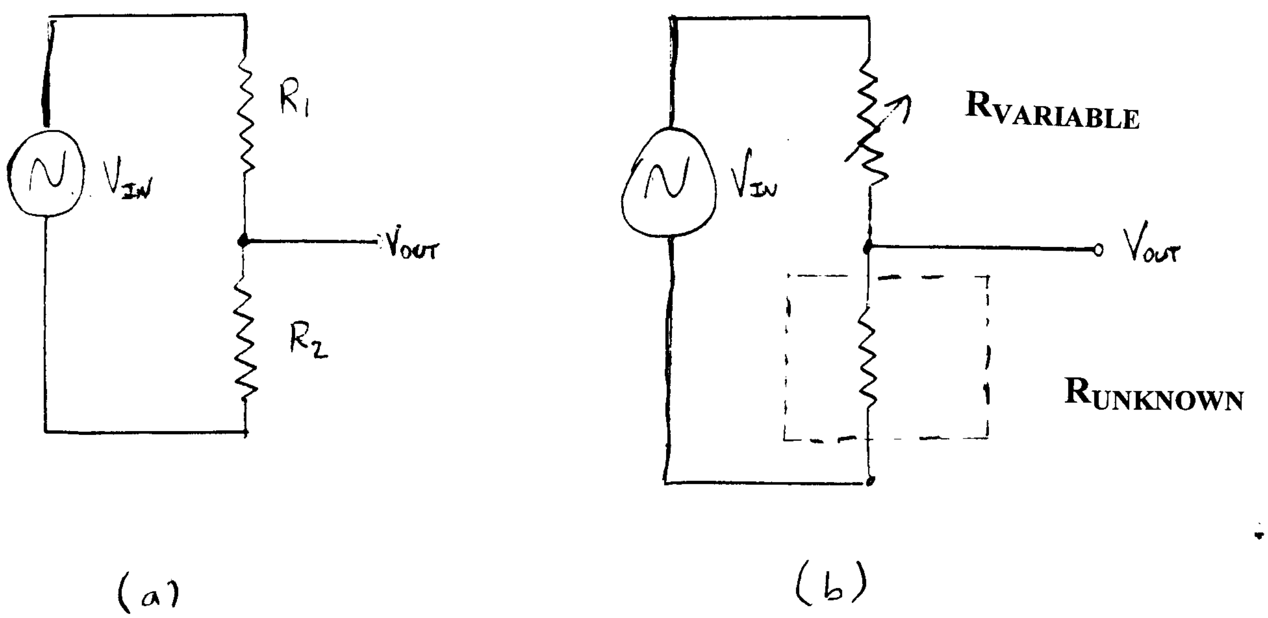

Figure 5

5.2.3 - Wheatstone Bridge

A Wheatstone bridge is illustrated in Figure 6. Note that when the variable resistance is adjusted such that $R_v = R_{unknown}$, the voltage difference between nodes 1 and 2 will be zero (this is clearly seen if each leg is considered to be an independent voltage divider, when the voltage dividers are identical the output voltages are identical). By using the unknown circuit impedance as one of the legs of the bridge, it is possible to adjust the variable resistor until $V_1 - V_2 = 0$. The Wheatstone bridge is the most accurate means of measuring input impedance because the voltage difference between nodes 1 and 2 is quite small when the bridge is adjusted to measure the circuit impedance. This small voltage can be made to approach zero by changing the variable resistor and thus the unknown resistance can be determined to the accuracy of the variable resistor used.

WHEATSTONE BRIDGE

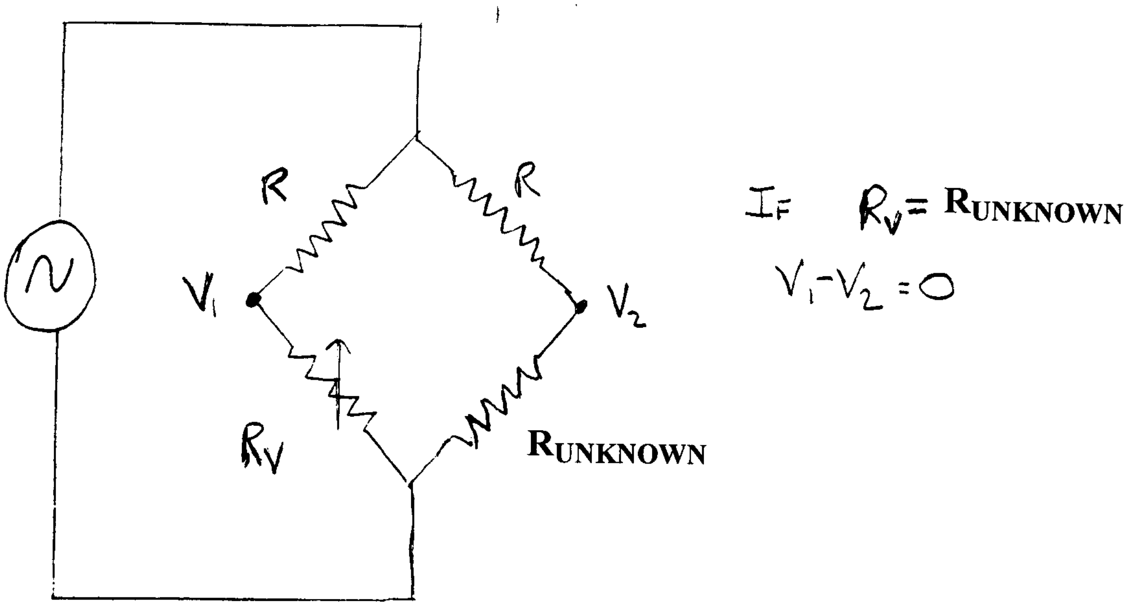

Figure 6

6. - Conclusions

Obtaining accurate measurements in the laboratory requires both knowledge of the laboratory instruments used and techniques for making measurements. Viewing the multimeter or oscilloscope as a "black box" which will provide answers is an approach that could lead to inaccurate and/or incorrect measurements.