

DEPARTMENT OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE  
**MASSACHUSETTS INSTITUTE OF TECHNOLOGY**  
CAMBRIDGE, MASSACHUSETTS 02139

Spring Term 2007  
6.101 Introductory Analog Electronics Laboratory  
Laboratory No. 2

## READING ASSIGNMENT

You should have read the diode reading assignments in the course outline before doing this lab.

For this laboratory, you will need to refer to the instruction manual for the Tektronix 577-177 or 575 Curve Tracers [manuals may be signed out at the stockroom window]. At a minimum, you should refer to the section of the manuals entitled **Applications** that describes how to set up the curve tracer to make measurements on specific devices such as diodes, bipolar transistors, etc. Since the 577-177 is a severely ergonometically-challenged design, it is strongly suggested that you use the model 575. Simplified instructions for the 575 curve tracers are chained to the instruments in the lab and are also available at the stockroom window. **DANGER: HIGH VOLTAGE is available on the collector terminals of any curve tracer depending on the setting of the collector voltage switch and the variable collector voltage pot position. Be sure to turn the transistor selector switch to the center "off" position before inserting or removing transistors, and to keep your hands free while applying voltage.** [This voltage is pulsed and is current limited, but may still "surprise" you if you touch the collector terminals!]

SPECIAL CURVE TRACER SETUP: One of the curve tracers, located in building 38, on the 6th floor, has been modified to allow the curves to be displayed on the new Tektronix sampling scopes. While the curves are not as clean as those displayed on an analog display, the new scopes do allow you to print your displays to a floppy disc. I suggest that you use .TIF file types for these curves. Instructions for using this hybrid curve tracer are posted on the equipment. This will save lots of sketching of device curves. There are 3 more curve tracers on the 5th floor.

## OBJECTIVE

**Diodes! Zener diodes! Bipolar Transistors! OpAmps! Power Supplies!** These are some of the fundamental devices and circuits in analog electronics. You will learn more about our test equipment, and you'll study some of the properties of the devices above. You will also build three [count 'em!] [3] different linear [non-switching] power supplies and compare them. You will learn how to display the input-output characteristics of some of these devices on our antique [but still very useful] curve tracers.

### Experiment 1: Diode Fundamentals: Building a Simple Log Amplifier.

In this experiment, you will learn more about the diode by studying a simple log amplifier.

#### **Simple Logarithmic Amplifier**

[You need to know that the voltage gain of this amplifier is  $A_V = \frac{V_{out}}{V_{in}} = -\frac{R_{diode}}{1.5k\Omega}$ ; you also need to

know that the inverting input, pin 2, is a virtual ground, in this case, for both AC and DC signals.]  
[We suggest that you express  $R_{diode}$  in more useful terms!]

1. Build the logarithmic amplifier shown in figure 1. **Q 1.1 What is the ideal input/output relationship  $V_{OUT}$  versus  $V_{IN}$  for this amplifier when the diode is biased with forward current?**  
**Q1.2 For what range of input voltages is there a logarithmic  $V_{OUT}$  versus  $V_{IN}$  relationship?**

2. When the diode is forward biased, the diode voltage/current relationship is given by:

$$I_D = I_S \left( e^{\left[ \frac{qV_D}{kT} \right]} - 1 \right) \approx I_S e^{\left[ \frac{qV_D}{kT} \right]}$$

where  $kT/q$  is the thermal voltage [ $\approx 26$  mV at room temperature] and  $I_S$  is the diode reverse saturation current which depends on the particular device, temperature, etc. **Q 1.3 When the diode forward current is increased by a factor of 10, how much does the diode voltage change?**

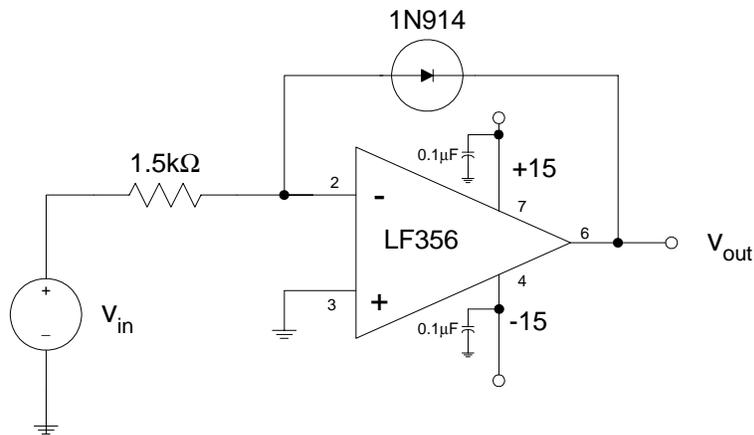


Figure 1: Circuit for Experiment 1

3. Plot the amplifier input/output relationship for  $10 \text{ mV} < V_{\text{IN}} < 1000 \text{ mV}$ . Use the DC offset adjustment control on your Function Generator to provide the DC voltage source. Make sure that the AC signal from the generator is turned off. To do this, press and hold the button labeled **OFFSET** for two seconds or until you hear a click. This will produce a pure DC output without any AC riding on top of it. Put one of your scope probes at the output of the amplifier to observe the output and to make sure that the only signal present is a DC signal. You should use your DMM to read first the input voltage [set to a convenient value], and then move the DMM to the output terminal to read the output DC voltage. Measure for several points per decade of input voltage, and use semi-log axes; this should result in a linear plot on semi-log axes.

4. **Q 1.4 Find the diode coefficient  $I_S$  from your data.** You will need to know that the current entering pin 2 of the operational amplifier is negligible compared to the current through the diode, at least at the higher DC input voltages. If you find that the logarithmic relationship between input and output disappears at low DC input voltages, it may be due to the fact that the pin 2 input current is the same order of magnitude as the current through the diode at low input voltages. This can still happen even though the LM356 has a JFET input stage, and thus very very low input bias current.

5. **Q 1.5 Measure an approximate temperature coefficient for the diode voltage, in  $\text{mV}/^\circ\text{C}$ .** [Hint: this can be done with the diode operating in your circuit; we want you to make a very rough estimate of the diode temperature coefficient. One possible method to change the temperature of the diode is to hold the diode between your thumb and forefinger with your fingers. Hold the diode until the output voltage stops changing.] **Q 1.6 Comment on the practicality of using this amplifier in a piece of equipment where the temperature may vary widely [for instance, in a piece of commercial electronics where the ambient temperature may vary from  $40^\circ\text{F}$  to  $150^\circ\text{F}$ ].**

6. Replace the 1N914 in your circuit with another 1N914 from your kit or from the drawers in the lab. On the same set of axes, plot the  $V_{\text{OUT}}/V_{\text{IN}}$  relationship. **Q 1.7 Observe if there are any differences between the two curves, and explain why.**

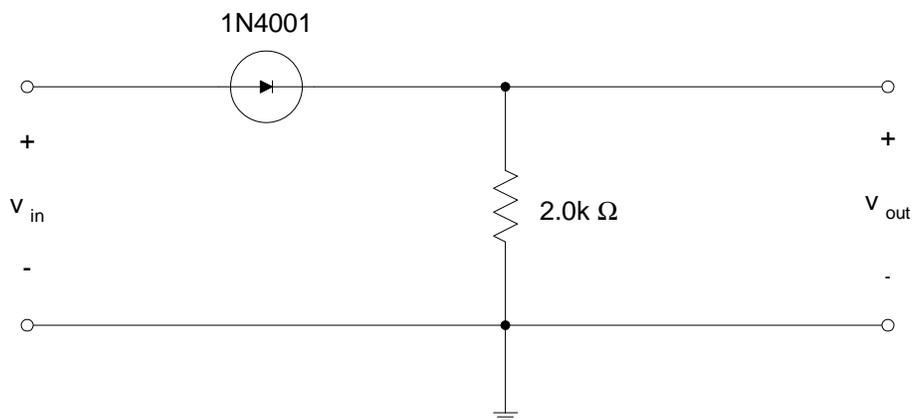


Figure 2: Circuit for Experiment 2.

**Experiment 2: Rectifier diodes.**

Note: There is one type 575 curve tracer in building 38, on the 6th floor and there are three type 575 curve tracers on the 5th floor. During this period of using the curve tracers, please do NOT turn them off once they have been turned on. Lab staff will turn them off at night, and the first person to use one during the day will turn them on.

1. Use the curve tracer to measure the characteristics of a 1N4001 rectifier diode from your lab kit. [Solder smaller diameter wires to the leads of your diode to get it to fit into the socket on the curve tracer; otherwise you will damage the curve tracer socket. Or, you can attach the diode to the curve tracer using the binding posts.] Refer to the section entitled SIGNAL AND RECTIFYING DIODES on page 33 of the 577-177 manual, or use the setup for Diode Forward Characteristic on page 4 of the manual attached to the 575 Curve Tracer **[attached]**. [The forward characteristics of a zener diode and an ordinary rectifier or signal diode are all measured in the same manner.] In your lab notebook [or on a separate piece of linear graph paper which you can insert in your lab notebook] plot the diode  $v - i$  characteristic for currents up to 20 mA. Repeat this plot on semi-log paper, using the log scale for the y-axis [current].
2. Construct the circuit of Figure 2. Apply a 100 Hz, 6 V peak-peak signal from the signal generator to the input,  $v_{in}$ . Measure the peak value of the output voltage  $v_{out}$  and the fraction of each cycle that  $v_{out}$  is zero.
3. Repeat part 2 for an input voltage of 20 V peak-peak.
4. Increase the frequency of the signal generator to 10 kHz. Observe that the diode does not switch off instantaneously and that in fact the diode actually conducts negative current for a short amount of time. This phenomenon is more pronounced at a frequency of 100 kHz. This is due to the fact that it is necessary to remove excess carriers from the junction of the diode before the diode can withstand reverse voltage. The time required to remove this charge from the diode is known as the reverse recovery time [referred to as  $t_{rr}$  on diode data sheets]. [ $t_{rr}$  is defined as the time it takes for the reverse current to drop to one-tenth of the forward current that was flowing before the voltage across the diode switches polarity.] Measure the amount of time during which the diode conducts reverse current with the input voltage at frequencies of 10 kHz and 100 kHz.
5. Replace the 1N4001 diode with the 1N914 diode from your lab kit. This diode is a signal or switching diode and is designed to operate at much faster switching times than the 1N4001. Repeat parts 2 through 4 with this diode. It may not however be possible to measure the recovery time for this diode.

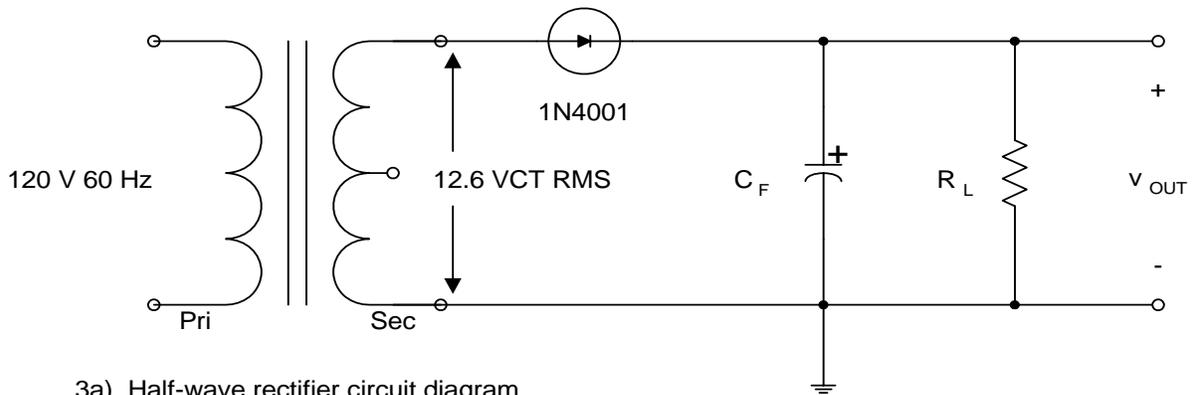
### **Experiment 3: Simple power supplies.**

In this experiment, you will build the three basic unregulated rectifier power supply circuits and compare their performance.

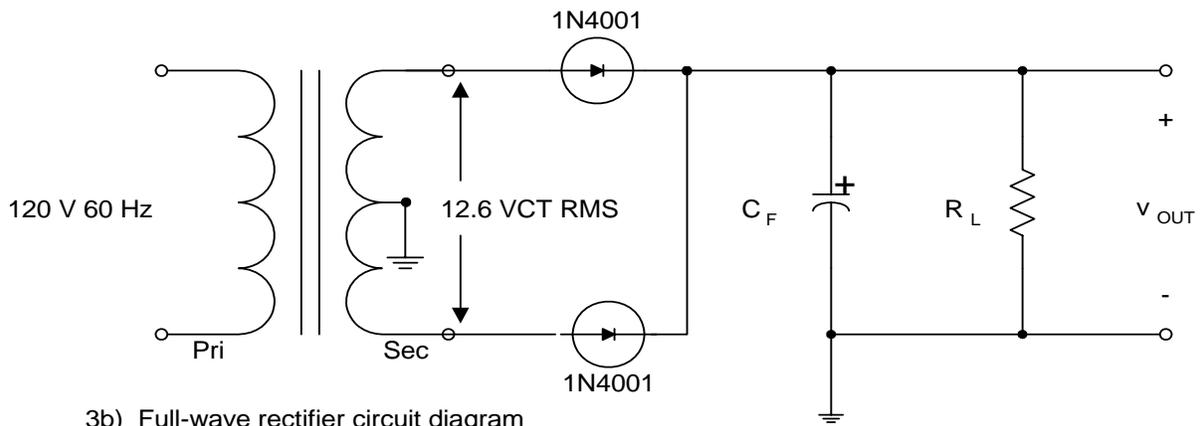
1. Use the 12.6 Volt center-tapped [RMS] power transformer terminals on your new [wooden case] 6.101 kit, or obtain a power transformer mounted in an aluminum box with a three-prong 120V AC plug, from the stockroom window, if you have one of the old 6.101 kits. [The third (round) prong is to ground the metal case and is NOT shown in the schematics below.] Construct the rectifier circuits of Figure 3, using  $R_L = 100 \Omega$  [you will need to obtain a special 5 watt resistor from the stockroom window] and use  $R_L = 1000 \Omega$  [**Q 3.1 What wattage will you need for this resistor?**]. Charts are provided for entering data. The first data should be taken

before you install any of the electrolytic filter capacitors. Use both your scope and your DMM on the AC range to measure the transformer secondary AC voltage,  $v_{\text{sec}}$ .

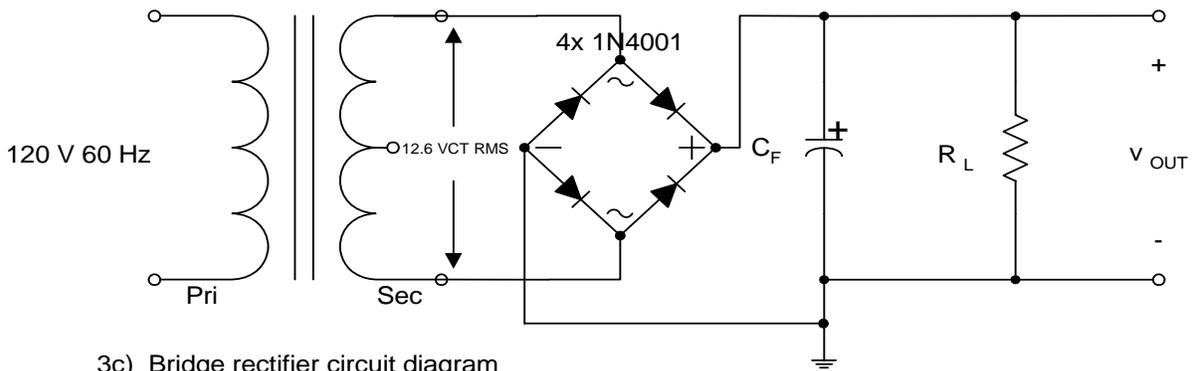
2. Sketch and label the DC output voltage  $v_{\text{out}}$  for each of the three connections, again without any filter capacitor installed. Label peak output values.
3. Calculate the average DC value from your sketches.
4. Move your scope probe and DMM to  $v_{\text{out}}$  and measure the actual values. Compare these to your calculated values.
5. Install the electrolytic capacitors and load resistors called for in the chart and make the measurements called for in the chart. **Be careful to get the polarity of the capacitor correct to avoid a possible explosion or other damage to you or the capacitor.** You should put your scope on AC coupling so as to see the ripple more effectively. It's a pretty small percentage of the total DC voltage output of these supplies.
6. Repeat step 2 with the smallest filter capacitor installed. Label peak-to-peak ripple values. Review your table data and draw some conclusions about low ripple voltage [desirable] versus capacitor size [a 1000  $\mu\text{F}/25\text{V}$  electrolytic costs \$0.84; 470  $\mu\text{F}/25\text{V}$  is \$0.34] and low ripple voltage versus number of diodes [a 1N4001 costs \$0.053]. **Q 3.2 What transformer secondary voltage would be required to make the output of the full-wave rectifier circuit equal to the output of the bridge or half-wave rectifier circuits?**



3a) Half-wave rectifier circuit diagram



3b) Full-wave rectifier circuit diagram



3c) Bridge rectifier circuit diagram

Figure 3: Circuits for Experiment 3

Table for Rectifier Circuits Data; 100 $\Omega$ Load						
Circuit	Capacitor size	$V_{\text{secondary}}$ [p-p]	$V_{\text{secondary}}$ rms [DMM]	$V_{\text{out}}$ DC [DMM]	$V_{\text{ripple}}$ [p-p]	Ripple frequency
Half-wave	none					
	470 $\mu\text{F}$					
	1000 $\mu\text{F}$					
	1470 $\mu\text{F}$					
Full-wave	none					
	470 $\mu\text{F}$					
	1000 $\mu\text{F}$					
	1470 $\mu\text{F}$					
Bridge	none					
	470 $\mu\text{F}$					
	1000 $\mu\text{F}$					
	1470 $\mu\text{F}$					

Table for Rectifier Circuits Data; 1000 $\Omega$ Load						
Circuit	Capacitor size	$V_{\text{secondary}}$ [p-p]	$V_{\text{secondary}}$ rms [DMM]	$V_{\text{out}}$ DC [DMM]	$V_{\text{ripple}}$ [p-p]	Ripple frequency
Half-wave	none					
	470 $\mu\text{F}$					
	1000 $\mu\text{F}$					
	1470 $\mu\text{F}$					
Full-wave	none					
	470 $\mu\text{F}$					
	1000 $\mu\text{F}$					
	1470 $\mu\text{F}$					
Bridge	none					
	470 $\mu\text{F}$					
	1000 $\mu\text{F}$					

1470 $\mu\text{F}$					
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### Experiment 4: Zener diodes.

As you will see, Zener diodes have a constant-voltage component of their reverse  $V - I$  characteristic which makes them useful as voltage regulators in simple power supplies and as voltage references in more complex power supplies and other applications.

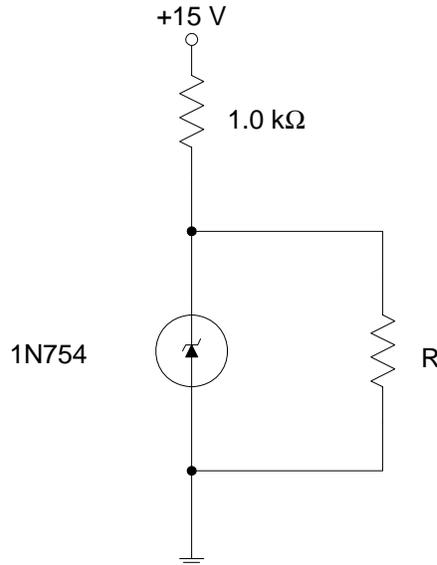


Figure 4: Circuit for Experiment 4.

1. Use the curve tracer to measure the characteristics of the 1N754 Zener diode from your lab kit. Refer to the section entitled ZENER DIODES on page 35 of the 577-177 manual, or page 5 of the 575 manual. [Your zener point will be a different voltage from that listed in the manual.] Plot the diode  $V - I$  characteristic for currents up to 20 mA in both forward and reverse directions.
2. Construct the circuit shown in Figure 4. Measure the voltage across resistor R for  $R = 10\text{k}\Omega$ ,  $R = 1.0\text{k}\Omega$ , and  $R = 100\ \Omega$ . [Q 4.1 What are the values of current flowing through the Zener diode for each of these three resistor values?]
3. Calculate the value of R in Figure 4 for which the Zener diode will no longer provide voltage regulation. Verify your calculation experimentally. [Q 4.2 Explain why the Zener stops regulating for certain values of R. Hint: think “voltage divider” or “current divider”.]

### Experiment 5: Bipolar transistors.

In this experiment, you will look at the basic characteristics of bipolar transistors. In later experiments you will look at some practical applications of these devices. For transistor number 1 only, sketch or draw or print the characteristic curves from the curve tracer display onto linear graph paper. 0.25 inch grid paper will be plenty good enough. You will need four [4] 2N3904 NPN transistors from your lab kit or from the drawers in the lab.

1. Use the curve tracer to measure the characteristics of a 2N3904 NPN transistor from your lab kit. Label this transistor as number 1 so that you can distinguish it from the remaining 2N3904 transistors in your lab kit. Refer to the section entitled BIPOLAR TRANSISTORS on page 19 of the 577-177 manual, or to pages 9ff in the 575 manual [page 9 attached]. Specifically, set the curve tracer to measure the transistor collector current  $I_C$  as a function of collector-emitter voltage  $V_{CE}$  for 10 steps of base current at  $5 \mu\text{A}/\text{step}$ . Set the MAX PEAK POWER WATTS control to 0.6 watts [model 577-177 only].

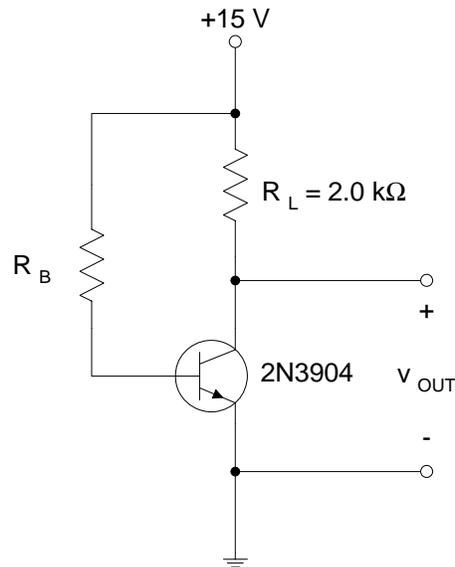


Figure 5: Circuit for Experiment 5.

2. Calculate the large-signal beta  $\beta_F = I_C / I_B$  of this transistor for each value of base current at collector-emitter voltages of 5 and 10 volts.

3. Calculate the small-signal beta  $\beta_o = \Delta I_C / \Delta I_B$  for the transistor as a function of base current for collector-emitter voltages of 5 and 10 volts.

4. Measure  $\beta_F$  for each of the remaining three 2N3904 transistors. Do not make an extensive set of measurements. The idea here is simply to compare the transistors and it will be sufficient to measure their betas at collector-emitter voltages of 5 volts and collector currents of 1 mA. Make sure to label each one in some fashion so that you can identify them for use in later experiments.

5. Select the 2N3904 transistor with the largest  $\beta_F$  based upon the results of your test. Construct the circuit of Figure 5. Based upon your measurements of this particular transistor, calculate the values of  $R_B$  such that the DC value of the voltage  $V_{out}$  will be approximately 7 V. Using the resistors in your lab kit, approximate this value of  $R_B$  in your circuit and verify your calculation. **Q 5.1 What factors determine how closely you can achieve the desired DC value of output voltage?**

6. Now select the 2N3904 transistor with the lowest  $\beta_F$  from your lab kit. Substitute this transistor for the one in your circuit and measure the value of the voltage  $V_{out}$ . Calculate the value of  $R_B$  required with this transistor to obtain an output voltage of approximately 7 V and again verify this

experimentally.

7. Select a 2N3906 PNP transistor from your lab kit. Using the curve tracer, measure the transistor collector current  $I_C$  as a function of collector-emitter voltage  $V_{CE}$  for 10 steps of base current at 5  $\mu\text{A}/\text{step}$ . Calculate the large-signal beta  $\beta_F = I_C / I_B$  of this transistor for each value of base current at collector-emitter voltages of -5 and -10 volts.

**The following note from Agilent [formerly Hewlett-Packard] explains how to read the value of the half-sine wave that the half-wave rectifier puts out, if you are having trouble getting the proper reading. The correct reading should be about the peak voltage divided by  $\pi$ .**

"The 34401A does not auto-range very well when measuring AC signals in DC mode. Since the AC does integrate down it chooses the wrong range, too small and then the input is overdriven. You have to manually select a range where the AC signal will not clip. For 17V peak you will need the 100V range. Then it should work correctly.

The integration time can be set from using the MEAS command, from the menu or from the keys with the blue Digits and the blue numbers 4,5,6. To use them press the shift key (also blue) then the key, for example if you want to change to 4.5 digits press shift then the down arrow key (it has the blue 4 above it).

The integration time will not effect this measurement unless it is less than a full period of the signal you are measuring. Since this is a 60Hz signal anything with an NPLC of 1 or more will work.

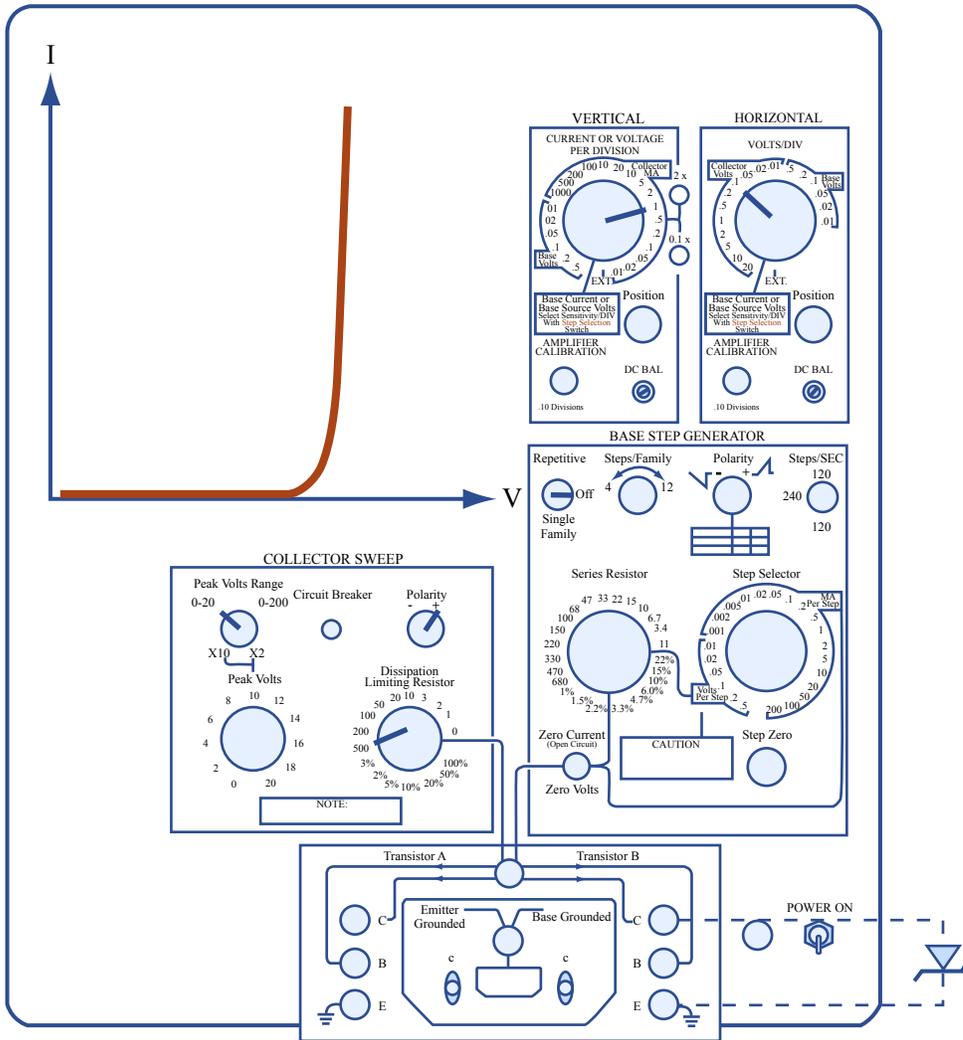
Yes we could have made the auto-range algorithm work on this kind of signal but it would have made it much slower and most users want it to work fast on DC.

Best regards,  
Hal Wright  
Agilent Technologies"

## HOW TO ADJUST THE STEP-ZERO ON THE 575 CURVE TRACER

1. First, make sure that the Vertical and Horizontal displays are zeroed: Hold the calibration switch for each one at zero, and position the dot so it lies in the lower left corner of the graticule for NPN devices, and in the upper right corner of the graticule for PNP devices. This is best done with no transistor under test [TUT] connected, and with the PEAK VOLTS pot turned fully CCW.
2. Next, insert, for this example, an NPN device into the test socket, and set the Vertical gain for 0.5mA/DIV, and the Horizontal gain for 2V/DIV. Set the base current for 0.005 mA/STEP, set the switch to "Repetitive" and turn the STEP ZERO control fully CW.
3. Adjust the STEPS/FAMILY pot fully CCW, to 4 STEPS/FAMILY. You will actually see FIVE steps, the  $I_B = 0$  step, and then the 4 steps corresponding to  $I_B = .005$  mA, .010 mA, .015 mA, and .020 mA.
4. Once you have verified that there are five steps, now increase the base current step selector to 0.01 mA/STEP. The upper steps will disappear but it will be easier to view the 0<sup>th</sup> step.
5. Push up the ZERO CURRENT switch and note where the 0<sup>th</sup> step falls. Release the switch and adjust the STEP ZERO pot CCW until the 0<sup>th</sup> step just moves down to the bottom line on the graticule [ $I_C=0$ ,  $I_B=0$ ]. DO NOT TURN THE KNOB ANY FURTHER!. If you continue to turn the knob, the 0<sup>th</sup> step trace will not go any lower, but the 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup>, 4<sup>th</sup> traces etc will move downward and thus screw up the calibration. You may want to alternate pushing up and releasing the ZERO CURRENT switch while you turn the step zero knob.
6. You should not have to repeat this calibration unless you use a PNP transistor or someone else comes along and decides to do this adjustment improperly!
7. When you view the curves for JFET's on this curve tracer, be sure to connect the 1000 ohm resistor across the base emitter terminals to convert base mA to gate volts. Then, when you do the calibration procedure above, just be sure to set the switch to ZERO VOLTS during the calibration procedure.

# TYPE 575 TEST SET-UP CHART



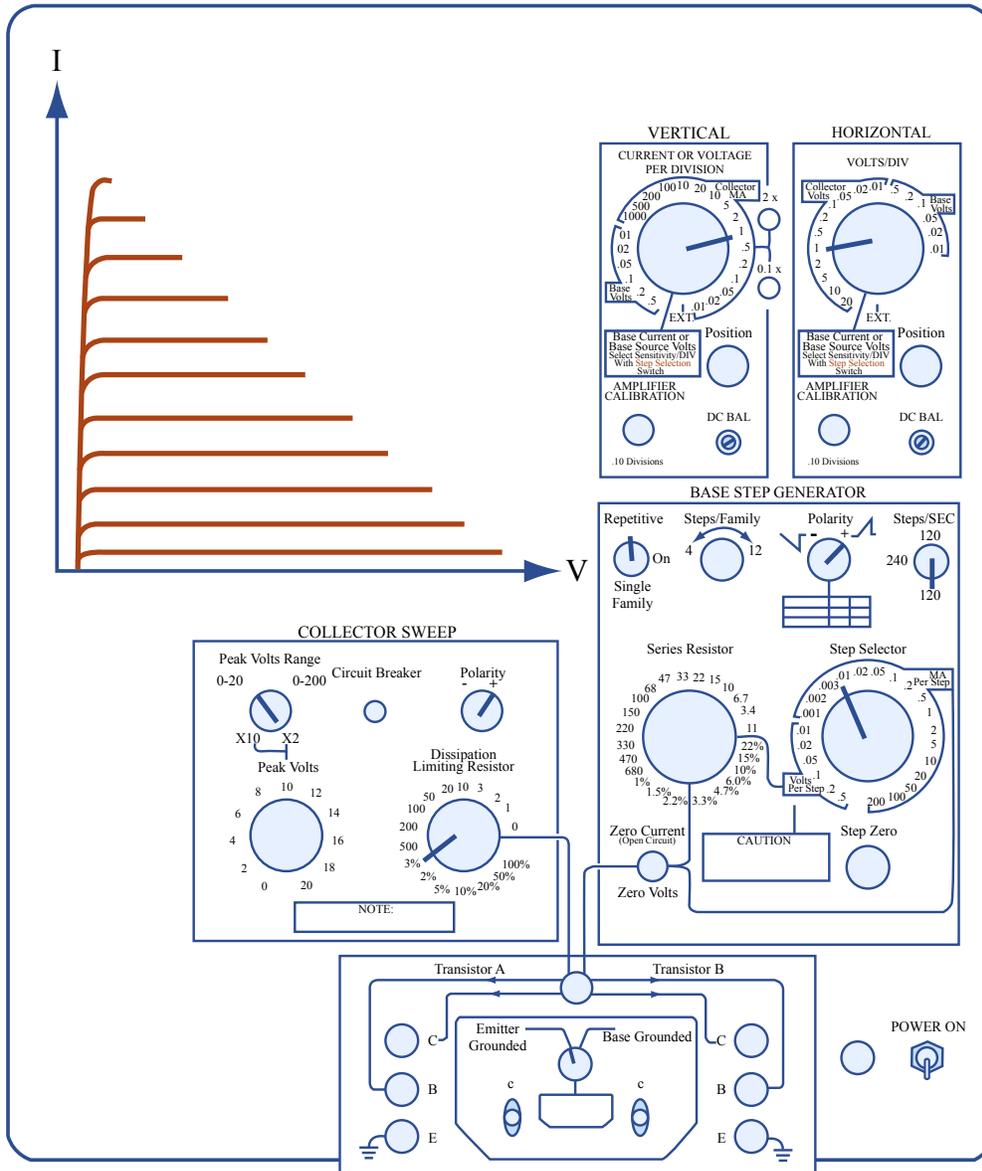
**DATA:** ZENER DIODE TYPE

FORWARD CHARACTERISTIC

$$\begin{aligned} \text{FORWARD IMPEDANCE} &= \frac{V}{I} \\ &= 280 \text{ OHMS AT } V_c = 700\text{mV} \\ & \quad I_c = 2.5\text{mA} \end{aligned}$$

Figure by MIT Opencourseware.

# TYPE 575 TEST SET-UP CHART



**DATA:** TYPE FORWARD CURRENT TRANSFER RATIO

COLLECTOR FAMILY, COMMON EMITTER

$$\text{Beta } (\beta) = \left. \frac{\Delta I_c}{\Delta I_b} \right|_{V_c = K} = h_{fe}, h_{FE}, h_{21e}$$

$$= \left. \frac{800\mu\text{A}}{10\mu\text{A}} \right|_{V_c = 5\text{V}} = 80$$

Figure by MIT Opencourseware.