Name: ________________________________

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

6.101 Introductory Analog Electronics Laboratory
Spring 2020 Laboratory No. 2 - Checkoff by Thu 2/20

READING ASSIGNMENT

You should have read the diode reading assignments in the course outline before doing this lab. Neamen: 1.2.4-1.5.5, 2.1-2.6

For this laboratory, you will be using model 575 curve tracer. Simplified instructions for the 575 curve tracers are chained to the instruments in the lab and posted on the web under the “Reference” link. These are very old tube type curve tracers but extremely easy to use.

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!]

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 different linear [non-switching] power supplies and compares 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

This circuit uses an operational amplifier (op-amps) with negative feedback. We will discuss op-amps in more detail in a future lecture. For this op-amp configuration, an inverter amplifier, the inverting input, pin 2, is a virtual ground, in this case, for both AC and DC signals. For a virtual ground, the voltage is ground, i.e. zero and the sum of the currents into the node is zero.

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?** [Answer next page- sign must be correct for credit]

Answer:

$(V_{in}\text{-}0v)/1.5k = I_d = I_s(e^{(0v-Vout)/Vth} - 1)$
V_D across the diode is just Vout because of the virtual ground at the summing junction.Neglecting the -1 term and rearranging, we have $V_{out} = -V_{th}\ln(V_{in}/(1.5k*Is))$ (eq. 2.1)

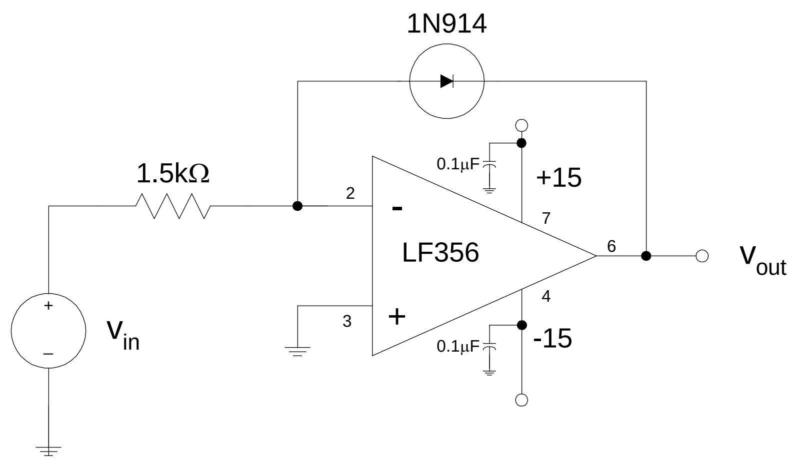


Figure 1: Circuit for Experiment 1

Checkoff: Demonstrate and explain the operation. [1 point]

Q1.2 For what range of input voltages is there a logarithmic V_{OUT} versus V_{IN} relationship?
Input should be positive in order to produce a logarithmic Vout versus Vin relationship. As the we see from eq. 2.1, you can't take the log of a negative number. Also, if Vin goes too high such that the Opamp is hitting its rails (ideally +-15V supply) then the circuit will not behave logarithmically.

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 [≈ 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 [in millivolts with correct sign]?**
If the diode forward current is increased by 10 (in other words, when Vin increases by 10x), then Vout should $\Delta V_{out} = -0.026(\ln(10V_{in}/(1.5k*I_s))-\ln(10V_{in}/(1.5k*I_s))) = -0.026*\ln(10) = -60mv$.

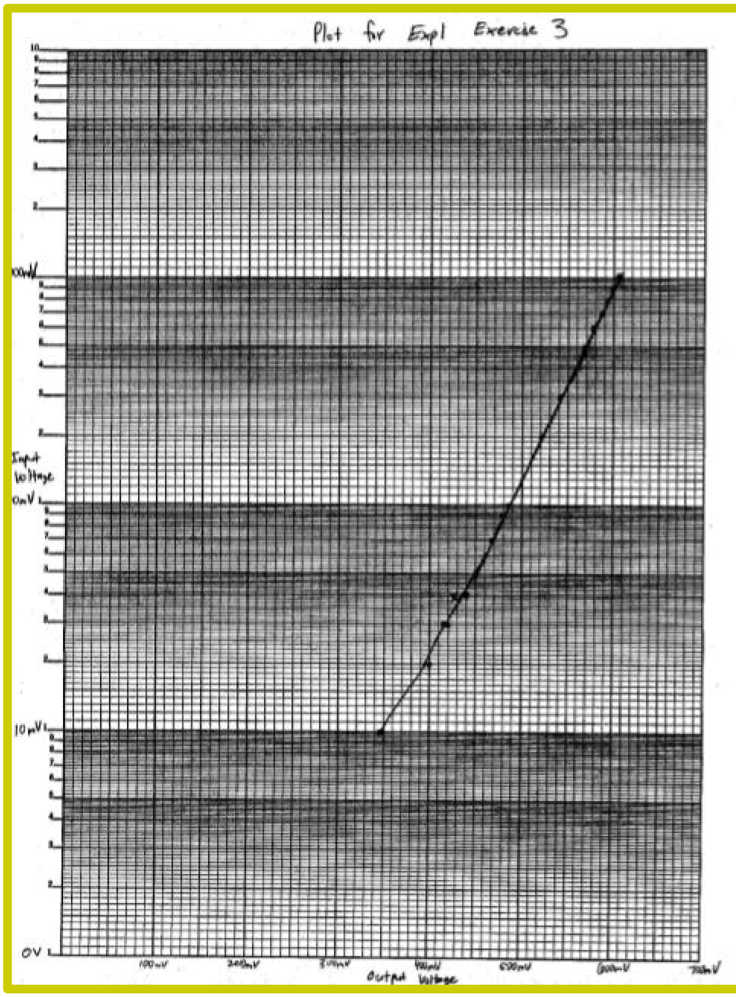
3. Plot the amplifier input/output relationship for 10 mV < V_{IN} < 1000 mV. Use the DC offset adjustment control on your Function Generator to provide the DC voltage source. Make sure that the AC signal from the generator is turned off. To do this, press and hold the button labeled ***OFFSET*** for two seconds or until you hear a click, for the HP 33120A; and use the UTILITIES menu for the Agilent 33220A. 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.

Sample Data and graph

here is a sample measurement run

Input Voltage	Output Voltage	Input Voltage	Output Voltage
10 mV	-344 mV	10 mV	-348 mV
20 mV	-396 mV	20 mV	-400 mV
30 mV	-416 mV	30 mV	-420 mV
40 mV	-436 mv	40 mV	-440 mV
50 mV	-448 mV	50 mV	-448 mV
60 mV	-460 mV	60 mV	-460 mV
70 mV	-464 mV	70 mV	-468 mV
80 mV	-472 mV	80 mV	-472 mV
90 mV	-476 mV	90 mV	-476 mV
100 mV	-484 mV	100 mV	-484 mV
200 mV	-520 mV	200 mV	-520 mV
300 mV	-540 mV	300 mV	-540 mV
400 mV	-560 mV	400 mV	-556 mV
500 mV	-568 mV	500 mV	-568 mV
600 mV	-576 mV	600 mV	-576 mV
700 mV	-588 mV	700 mV	-584 mV
800 mV	-592 mV	800 mV	-592 mV
900 mV	-600 mV	900 mV	-596 mV
1000 mV	-604 mV	1000 mV	-600 mV
2000 mV	-636 mV	2000 mV	-636 mV
3000 mV	-656 mV	3000 mV	-656 mV
4000 mV	-672 mV	4000 mV	-672 mV
5000 mV	-688 mV	5000 mV	-684 mV
6000 mV	-696 mV	6000 mV	-692 mV
7000 mV	-704 mV	7000 mV	-704 mV
8000 mV	-712 mV	8000 mV	-712 mV
9000 mV	-716 mV	9000 mV	-716 mV
10000 mV	-724 mV	10000 mV	-724 mV

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.

Is: when Vin=1V. $I_s = V_{in}/(1.5k)*e^{-(V_{out}/V_{th})}$ = 5.43E-14 = 0.05pA

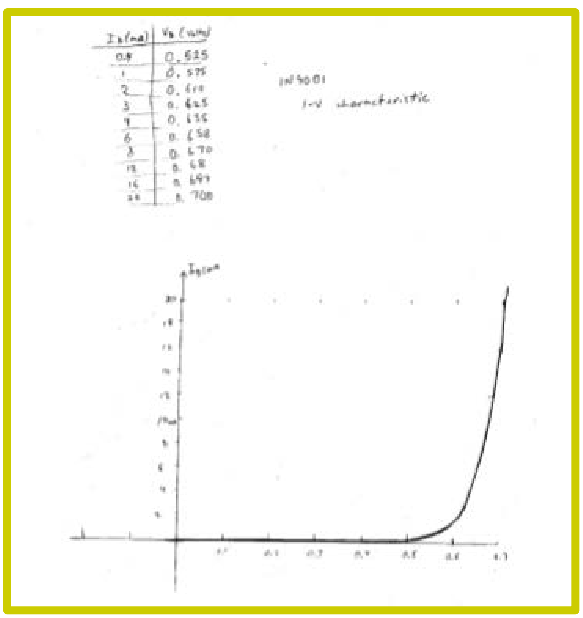
5. **Q 1.5 Measure an approximate temperature coefficient for the diode voltage, in mV/^{o}C.** [Hint: this can be done with the diode operating in your circuit; we want you to make a very rough estimate of the diode temperature coefficient. One possible method to change the temperature of the diode is to hold the diode between your thumb and forefinger. Hold the diode until the output voltage stops changing.] *This circuit's characteristics (gain, etc) will drift with temperature much more so than will an amplifier using only resistors. Also, with resistors, at least both the input and feedback resistors will drift somewhat together. Therefore this is not a good circuit to use if stable, repeatable results are a high priority. Real test equipment often uses an "oven". The sensitive components are heated up to something much higher than ambient temperature, say 150ºC and maintained at that temperature by a thermostat to control thermal drift.*

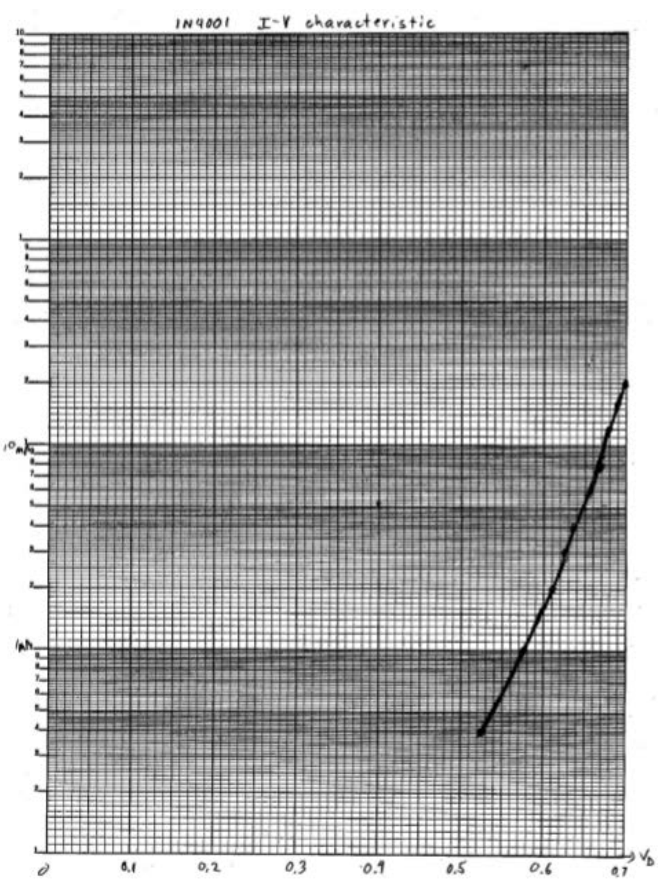
Coefficient for the diode voltage = ________ mV/^{o}C

Experiment 2: Rectifier diodes.

Note: There are two 575 curve tracer in room 38-601. **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 persons 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 the parts kit. [The 1N4001 have heavy gauge wires. Attach the diode to the curve tracer using the binding posts.] Use the setup for the Curve Tracer is attached at the end of this writeup. [The forward characteristics of a zener diode and an ordinary rectifier or signal diode are all measured in the same manner.] On semi-log paper, using the log scale for the y-axis [current] plot the diode v - i characteristic for currents up to 20 mA





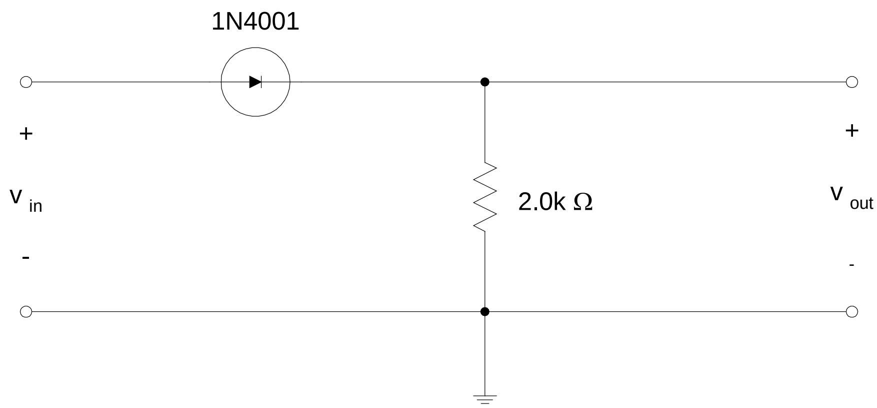


Figure 2: Circuit for Experiment 2.

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. Excess carriers must be removed 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 the kits. 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; it's very fast!

<u>Experiment 3: Simple power supplies.</u>

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

1. Use the 12.6 Volt RMS center-tapped power transformer terminals on your 6.101 kit, construct the rectifier circuits of Figure 3, using R_L = 100 Ω [there are special 5 watt resistor [white] in the lab] and using R_L = 1000 Ω [**Q 3.1 What wattage will you need for the 1000Ω resistor? The resistors in lab are generally ¼ watt resistors.**].

   The highest peak voltage Vout we can achieve occurs with the halve-wave rectifier configuration because Vout is the full secondary and only there is only 1 diode drop Vd. We take the average value to be the peak value, which basically assumes that the filtering is adequate such that ripple is negligible. When this assumption is violated, the dissipated power can only be lower. Max

Vout is Vrms V V d 12.6 * 2 - = 12.6 * 2 - 0.6 = 17.22 A 0.5 Watt resistor will be adequate.

Max Vout is $12.6Vrms * \sqrt{2} - V_d = 12.6 * \sqrt{2} - 0.6 = 17.22V$

$$P = \frac{V^2}{R} = \frac{17.22^2}{1000} = 0.30WATTS.$$ A 0.5 Watt resistor will be adequate.

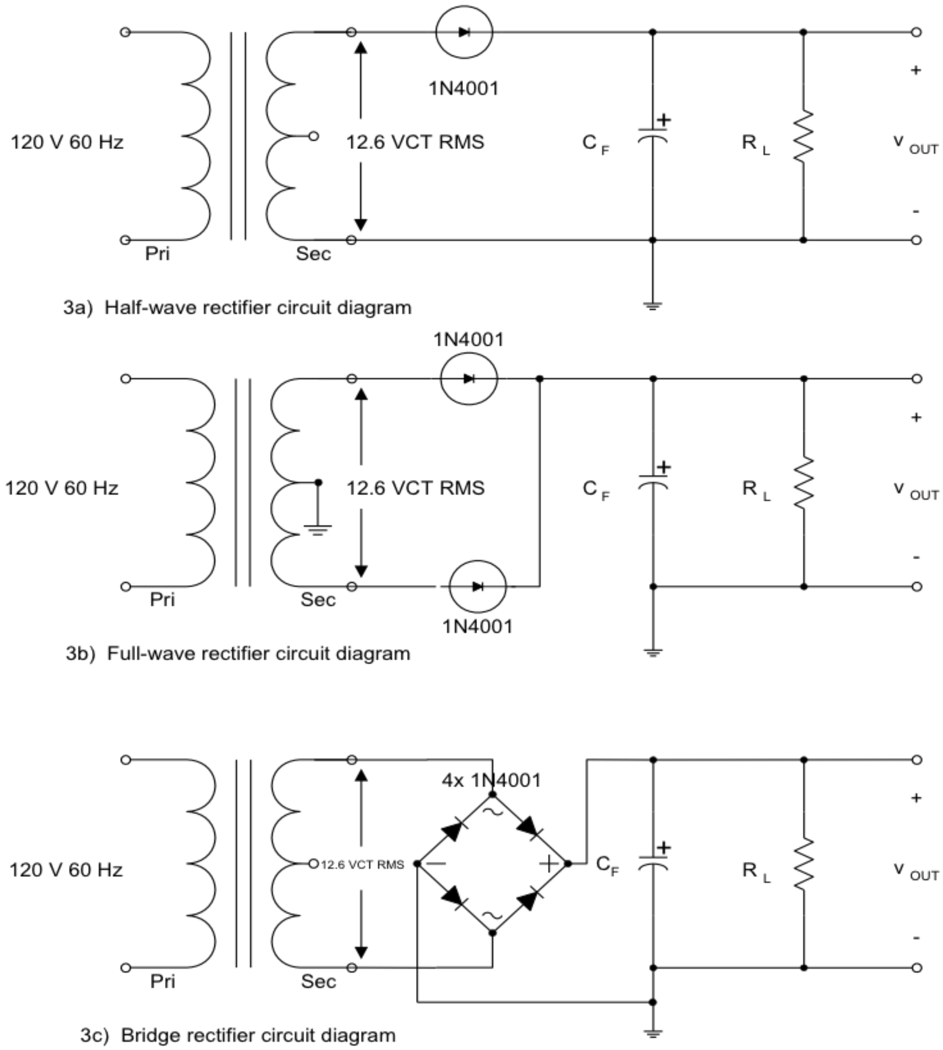


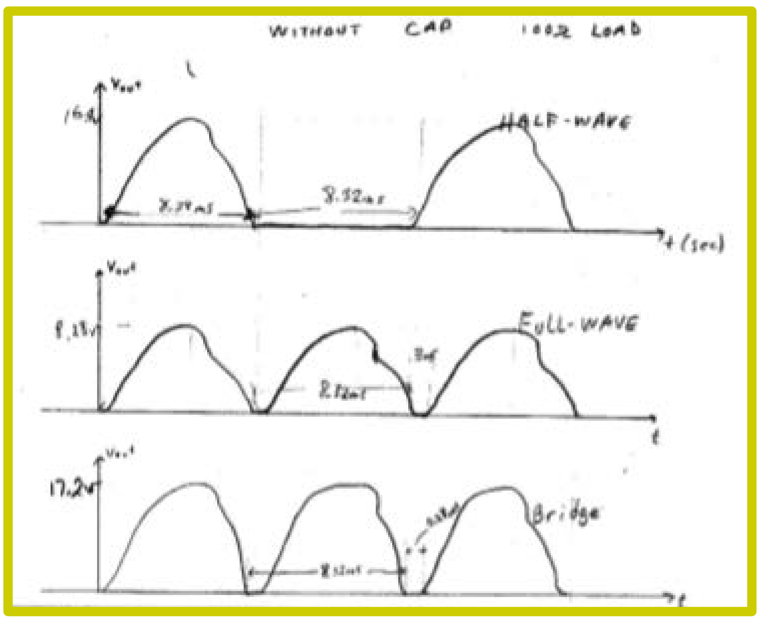
Figure 3: Circuits for Experiment 3

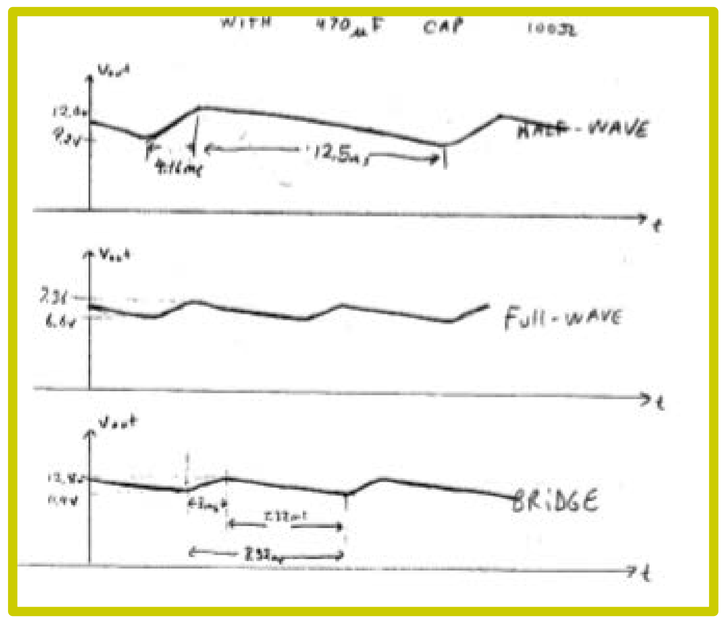
Charts are provided for entering data (page 8). The first data should be taken before you install any of the electrolytic filter capacitors. Use both your scope and your DMM on the AC range to measure the transformer secondary AC voltage, $v_{sec.}$

[From the "more than you wanted to know" department: the next few paragraphs are optional but will add to your technical background.] Conduction angle is the fraction of a wave that is conducting current with full conduction 360 degree corresponding to a full cyle. The conduction angle can be measured with one of ancient but still working HP 428B Clip-On DC Milliammeters. Some things are difficult to measure without a current probe, and conduction angle is one of them. Gently open the jaws of the current probe and clamp it over the diode anode lead, or a wire that feeds the anode. [The probe goes over or surrounds the wire, it does not clamp ***ON*** the wire.] We aren't really interested in the reading on the meter [set the range switch so it won't "pin" the meter to the right or read below zero on the left, and try to set the range switch so that you get a meter reading in the upper part of the meter scale (more than half-way up the scale)]. At that point, get a BNC-BNC cable and connect the "output" jack on the HP 428B front panel to one of the scope inputs. This will allow you to view and measure the conduction angle easily. [This is basically a substitute for a very expensive oscilloscope current probe, but it is 3dB down at 400 Hz, so use it wisely!] Try not to damage the ferrite parts that form the jaws of the clamp….close and open it carefully. Be sure to zero the HP 428B].

If you have any problems with the current reading, turn the 428B around and insert the probe in the hole in the back of the meter to degauss it [remove the residual magnetism]. Follow the instructions on the back of the meter.

2. Sketch and label the DC output voltage v_{out} you've observed 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 and label on the sketches.

3. calculating DC voltage of each rectifier without Capacitors.

With 100Ω load

half wave: $\frac{Vp}{\pi} = \frac{16.4}{\pi} = 5.22\,V$

Full wave: $\frac{2Vp}{\pi} = \frac{2*8.28}{\pi} = 5.27\,V$

Bridged: $\frac{2Vp}{\pi} = \frac{2*17.2}{\pi} = 10.95\,V$

With 1000Ω LOAD

half wave: $\frac{Vp}{\pi} = \frac{18.3}{\pi} = 5.82\,V$

Full wave: $\frac{2Vp}{\pi} = \frac{2*8.28}{\pi} = 5.63\,V$

Bridged: $\frac{2Vp}{\pi} = \frac{2*17.5}{\pi} = 11.14\,V$

4. Connect your scope probe and DMM to V_{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 μF/25V electrolytic costs $0.84; 470 μF/25V 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? ______25.2VAC_______________

Table for Rectifier Circuits Data; **100 Ω Load**							
Circuit	Capacitor size	$V_{secondary}$ [p-p]	$V_{secondary}$ rms [DMM]	V_{out} DC [DMM]	V_{ripple} [p-p]	Ripple frequency	Conduction Angle (optional)
Half-wave	none						
	470 μF						
	1000 μF						
Full-wave	none						
	470 μF						
	1000 μF						
Bridge	none						
	470 μF						
	1000 μF						

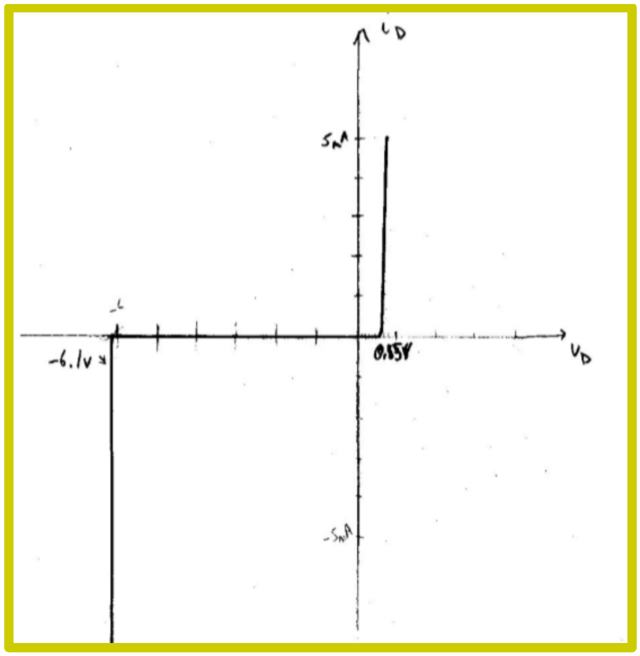
Table for Rectifier Circuits Data; **1000 Ω Load**							
Circuit	Capacitor size	$V_{secondary}$ [p-p]	$V_{secondary}$ rms [DMM]	V_{out} DC [DMM]	V_{ripple} [p-p]	Ripple frequency	Conduction Angle (optional)
Bridge	470 μF						
	1000 μF						

Experiment 3 Checkoff: Measure and display ripple with 100 ohm load and 470 uf capacitor. [1.7 points]

Experiment 4: Zener diodes.

As you will see, Zener diodes have an almost 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.

1. Use the curve tracer to measure the characteristics of the 1N754 Zener diode from the drawers. See the 575 settings attached at the end. [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 = 10kΩ, R = 1.0 kΩ, and R = 100 Ω. [**Q 4.1 What are the values of current flowing through the Zener diode for each of these three resistor values? Be sure to measure the +15v supply first.**]

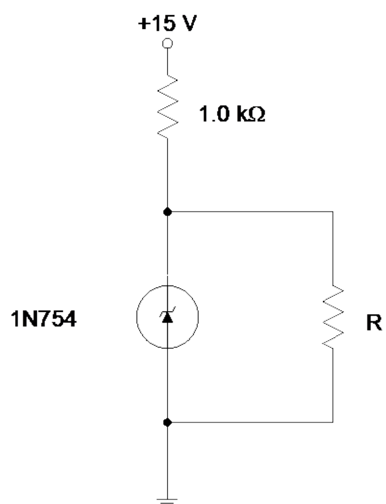


Figure 4: Circuit for Experiment 4.

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 What is the value and explain why the Zener stops regulating for certain values of R. Hint: think "voltage divider" or "current divider".**]

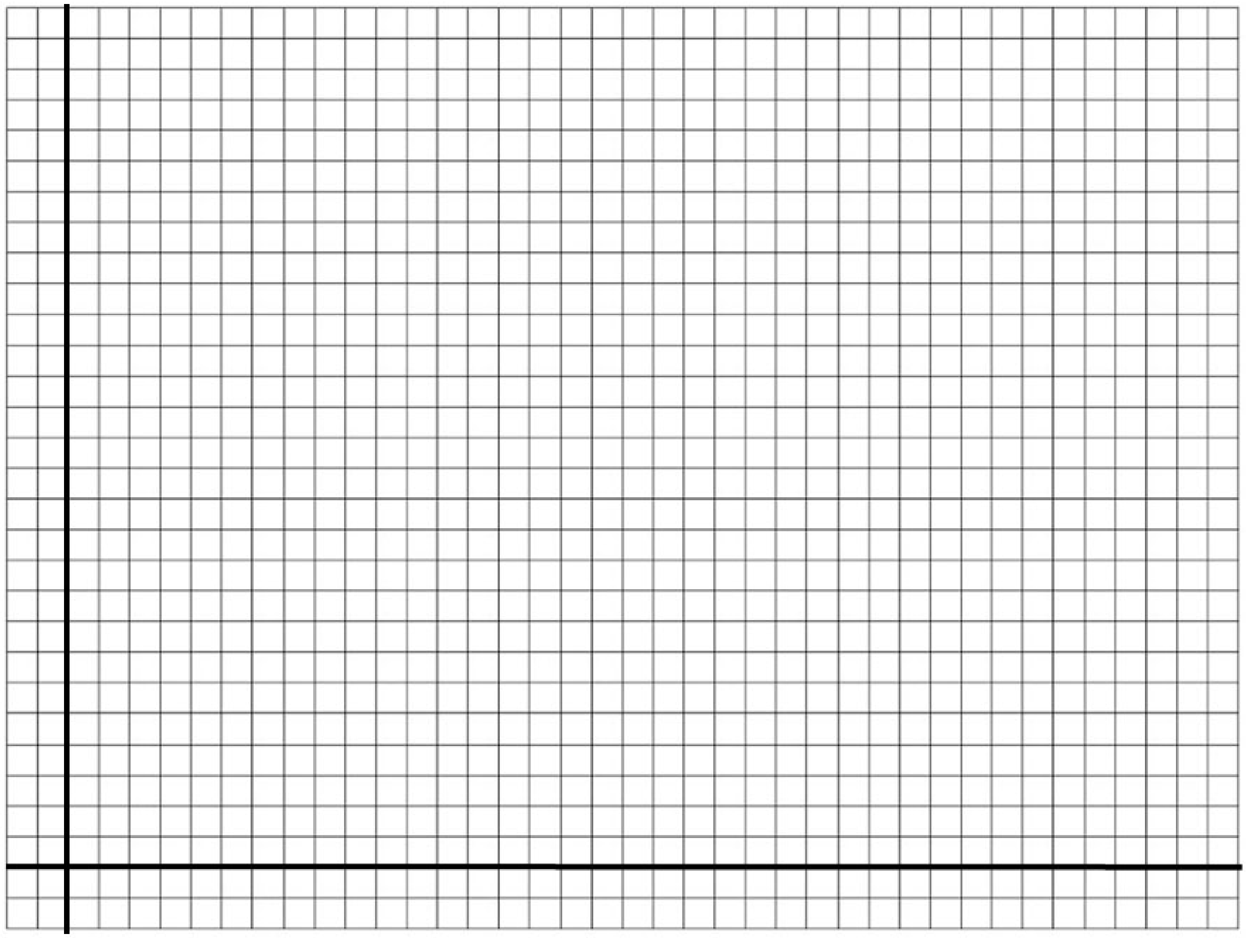
We know that the total current I = (15V-VR)/1k. We then know that the current through the diode is the total current minus the current through the bottom resistor. Id = I_T – V_R/R

	R=10kΩ	R=1.0kΩ	R=100Ω
V_R	6.69V	6.67V	1.35V
I(total)	8.31mA	8.33mA	13.65mA
I_d	7.64 mA	1.66 mA	0.15 mA

I measured Vz to be about equal to –6.0 V Vz = -6.0V. so the diode is on the verge of regulating when VR = 6.0V = (15V*R/(R+1.0k) => R = 667Ω

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 be sure to label the axis



1. Use the curve tracer to measure the characteristics of a 2N3904 NPN transistor from the lab kit. Label this transistor as number 1 so that you can distinguish it from the remaining 2N3904 transistors in the lab kit. The setup for the Curve Tracer is attached near the end of the writeup. 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 μA/step.

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. Use your M3 Electronix semiconductor analyzer to verify that your calculation using the curve tracer is in the ballpark.

4. Measure β_F for each of the remaining two 2N3904 transistors using M3 Electronix semiconductor and the "All Purpose Tester" on the TA bench. Make sure to label each one in some fashion so that you can identify them for use in later experiments. R_B will be calculated in exercises 5 & 6.

Transistor	**β_F Curver**	**β_F M3**	**All Purpose**	**R_B**

	Tracer	Analyzer	Tester	
1				
2				
3				

5. Select the 2N3904 transistor with the largest β_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 the lab kit, approximate this value of R_B in your circuit and verify your calculation. Enter the value of R_B in the table above.

Q 5.1 What factors determine how closely you can achieve the desired DC value of output voltage?

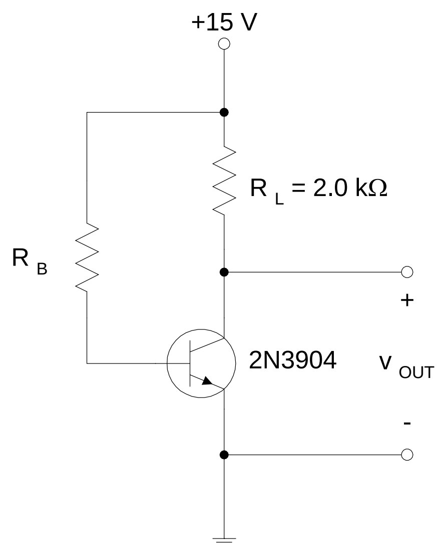


Figure 5: Circuit for Experiment 5.

Checkoff: Display V_{out} at 7V and show value for R_B [2.3 points].

6. Now select the 2N3904 transistor with the lowest β_F from the parts 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. Enter the values in the table above.

7. Select a 2N3906 PNP transistor from the kit. Using the curve tracer, [NB the polarities of the base current and collect voltage must be switched] measure the transistor collector current I_C as a function of collector-emitter voltage V_{CE} for 10 steps of base current at 5 μA/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, and now Keysight] 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 π.

"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"

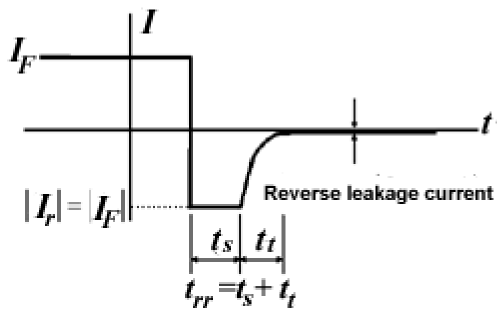
Reverse Recovery Time

Question:
Please explain the so-called "reverse recovery time" (t_{rr}) specification in the specification sheet of diodes.

Answer:

Ideally, a diode is (a) a perfect conductor when it is forward biased, (b) a perfect insulator when reverse biased, and (c) the transition from conductor to insulator is instantaneous upon a forward bias/reverse bias switch. Practical diodes don't display these ideal characteristics, and the question above is related to the transition (switching) time from conduction to open circuit when the bias is reversed.

The figure below shows what happens when the diode bias is switched from forward to reverse. At the switch time, the current reverses and stays at a constant level for a period of time called the storage time, t_s. During this time the diode acts essentially as a short circuit. Then the current decreases to the reverse leakage current value. This latter time is called the transition time. The sum of the storage and transition times is the reverse recovery time. It depends on the forward current, and data sheets give the reverse recovery time along with the test conditions.



Why does a diode behave this way? When pn junction is forward biased, a large number of electrons are injected into the p-material, and a large number of holes are injected into the n-material of the pn junction. When the diode is then reverse biased, these stored minority carriers must return to the opposite material. The time it takes for the electrons to move from the p-material back to the n-material and the holes to move from the n-material to the p-material is the storage time, and is determined by the geometry of the pn junction. Once this migration is complete, the electrons diffuse to, and recombine at the anode, and the holes diffuse to and recombine at the cathode until there are no more of the original stored carriers left. This time is the transition time, and is determined by the geometry and doping levels of the p- and n-materials.

The reverse recovery times for pn junction diodes are a few microseconds for general-purpose rectifier diodes such as the 1N4001. When a diode is employed to rectify a 60-Hz voltage in a power supply, a reverse recovery time of 1 microsecond is irrelevant. However, when the diode is used as a switch in a circuit that runs at 100 KHz, then 1 microsecond is a substantial part of the conduction cycle, and the diode will dissipate a lot of energy. In switching applications such as DC-DC converters this can seriously impact efficiency. By manipulating doping levels and junction geometry one can manufacture semiconductor junction rectifiers with much smaller reverse recovery times. For example, the industry standard 1N4933 fast rectifier has a reverse recovery time of 200 ns. For small-signal (as opposed to power rectification) applications pn junction diodes can be made quite fast-the widely used 1N4148 small-signal diode has a reverse recovery time of 4 ns. However, all pn junctions have by necessity stored minority carriers when forward biased, so there are limits on what can be done. Additionally, the faster speed comes at the expense of higher forward voltage drop and higher reverse leakage currents.

For really small switching times, Schottky barrier diodes are used. These diodes are not pn junctions, but consist of a semiconductor-metal junction, and there are no stored minority carriers. Switching times can be as small as a few hundred picoseconds. This is very useful when protecting MOS devices, and in lower level switching and steering applications. Apart from fast switching times, Schottky diodes also have the desirable quality of low forward voltages. This makes them attractive for power rectifier applications.

Description	General Purpose Rectifier	Fast Switching Rectifier	Small Signal Diode	Schottky Diode
Sample Device	1N4001	1N4933	1N4148	ZC2800
Maximum DC/Average Forward Current	1 A	1 A	300 mA	15 mA
Maximum Reverse Voltage	50 V	50 V	75 V	70 V
Reverse Leakage Current @ 25 °C and VR = 20 V	50 nA	200 nA	5 nA	200 nA
Forward Voltage	~0.7 V	1 V @ IF = 1A	1 V @ IF = 10 mA	0.41 V @ 1 mA
Reverse Recovery Time	2 µs	200 ns	4 ns	1 ns
Cost	20 cent	15 cent	25 cent	100 cent

Some characteristics of general-purpose/fast rectifier and general-purpose/Schottky diodes.

The above article was written by Anton Kruger, and the original may be found at:

http://www.chipcenter.com/eexpert/akruger/akruger004.html

Zener (shown) & 1N4000 Diode Setup

NPN Setup


TYPE 575 TRANSISTOR-CURVE TRACER
VERTICAL
CURRENT OR VOLTAGE PER DIVISION
HORIZONTAL
VOLTS/DIV
BASE STEP GENERATOR
STEPS/FAMILY
POLARITY
STEPS/SEC
FOCUS
INTENSITY
ASTIGMATISM
SCALE ILLUM.
COLLECTOR SWEEP
PEAK VOLTS RANGE
CIRCUIT BREAKER
POLARITY
PEAK VOLTS
DISSIPATION LIMITING RESISTOR
SERIES RESISTOR
STEP SELECTOR
ZERO CURRENT
ZERO VOLTS
STEP ZERO
PLEASE LEAVE ME ON
DANGER
HIGH VOLTAGE
TRANSISTOR A
TRANSISTOR B
EMITTER GROUNDED
BASE GROUNDED