2

Linear Power Supply

In this lab you will construct a regulated DC power supply to provide a low-ripple adjustable dual-output voltage in the range ±9-12 VDC at 0.2 Amps (maximum) load current from a 120 VAC power outlet. This will be used to provide power to circuits you will construct in later labs in ECE 2.

Linear power supplies of the type described here are essential components of any microelectronic system. This lab is intended to provide a basic understanding of the design and operation of linear supplies, and techniques for construction of hardwired electronic circuit modules. In this lab you will gain experience with:

- Power transformers
- Diode bridge rectifiers
- Capacitive loading for ripple rejection
- Use of electrolytic capacitors
- Power resistors
- Use of IC voltage regulators
- Including simple LED indicators
- Basic soldering techniques

The objective of the lab is not simply to create a working circuit; it is to *learn* about circuits! So, as you progress through the lab, try to understand the role of each component, and how the choice of component value may influence the operation of the circuit. Ask yourself questions such as: Why is this resistor here? Why was this particular integrated circuit chosen? How could the system be improved? It is only when you can answer such questions that you will truly understand the lab and progress towards designing your own circuits.

Linear Power Supply

1

Pre-lab Preparation

Before Coming to the Lab

Read through the lab experiment to familiarize yourself with the components and assembly sequence. Before coming to the lab, each lab group should obtain a parts kit from the ECE Shop. If you have not yet done so, remember to purchase a soldering iron (one for each group) stand, and roll of solder, as well as small tools (wire cutter/stripper, needle-nose pliers, screwdriver, etc.). Beginning in 2007, all ECE labs will use lead-free solder, and this requires a somewhat more expensive soldering iron.

Optional: simulate the regulated supply using Circuit Maker™ or MultiSim (circuit files available on the course web site).

Parts List

The ECE2 lab is stocked with resistors so do not be alarmed if you kits does not include the resistors listed below.

Laboratory #2		
Dual Regulated Power Supply		
Qty	**Description**	**Circuit**
1	Power Transformer (output 18VCT @1A)	T1
1	In-line 3AG fuse housing, #18 wire	
1	120V 3-prong power cord	
1	AC power switch, SPST	
2	3AG Fuse, 1A 250V	
4	Silicon Rectifier Diodes, 1N4005 (1A, 300V)	D1-D4
8	1000uF >25V electrolytic capacitors (radial lead)	Cp1-2, Cn1-2
1	LM317T 3-terminal Adj. Pos Regulator (TO-220)	U1
1	LM337T 3-terminal Adj. Neg. Regulator (TO-220)	U2
2	TO-220 Heatsink, PC mount	
2	Mounting hardware for TO-220 heatsink	
2	240-Ohm 1/4 Watt resistor	R1,R4
2	5k trimpot	R2,R6
1	Red LED (20mA)	D5
1	Green LED (20mA)	D6
2	470-Ohm 1/4 Watt resistor	R3,R5
2	0.1uF mylar capacitor	C1,C3
2	10uF 25V electrolytic capacitor (PC lead)	C2,C4
1	0.05-Ohm 2 Watt resistor	Rs
1	4.5" x 8.5" vectorboard	
4	Rubber feet	
15	flea clips	
12"	#18 stranded wire (black)	
12"	#18 stranded wire (red)	
2	6/32 1/4" machine screw	
2	6/32 nuts	
3	5-way binding posts (red, green, black)	

Schematic for Lab #2

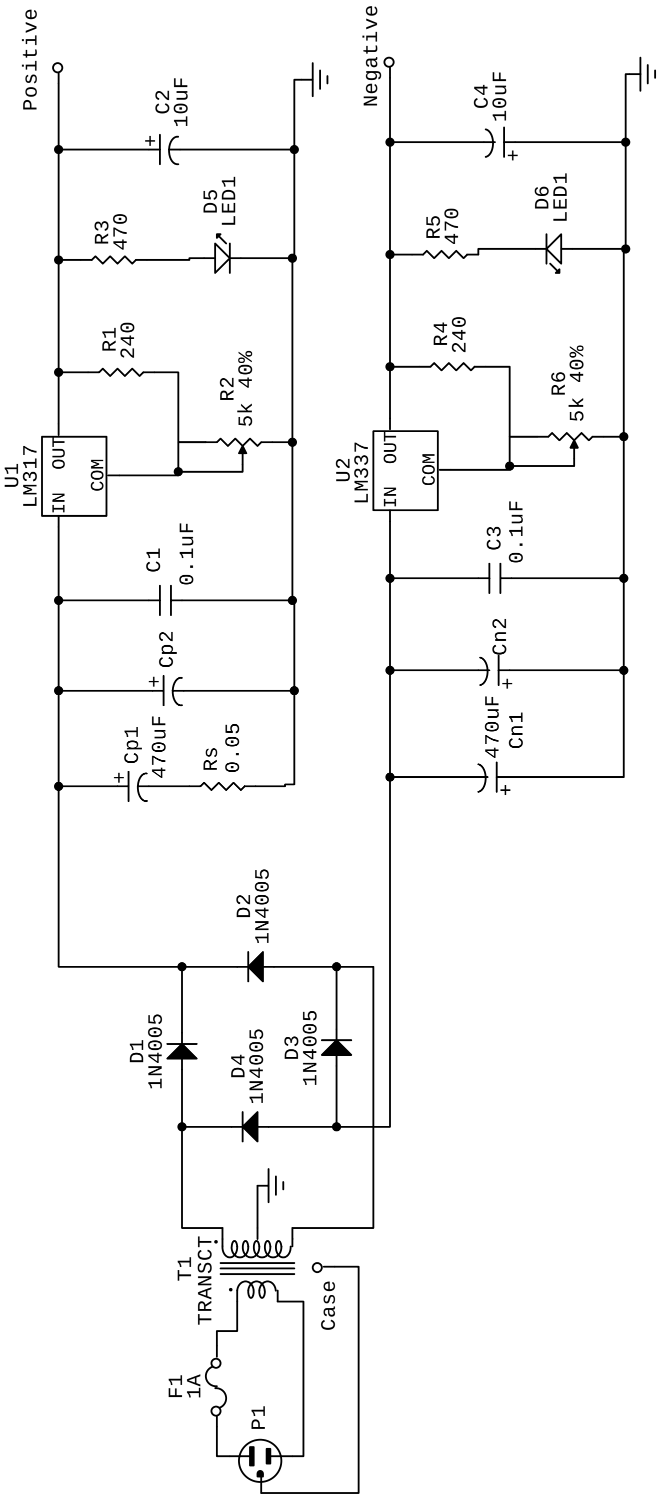


Figure 2-1 – Complete schematic of ECE 2 Dual-Output Adjustable Linear Regulated Power Supply.

Background information

Basics of Linear Power Supply Design

The simplest and most common type of DC power supplies is a "linear" system, shown schematically in Figure 2-2.[1] First a transformer is used to "downconvert" the AC line voltage to a smaller peak voltage V_m, which is usually around 2-3 Volts larger than the ultimately desired DC output. A diode circuit rectifies the AC signal, producing waveform with large DC component. A capacitor filter bank is then used to "smooth" or "filter" the rectified sinusoid. Under normal loading conditions there is always some residual periodic variation or "ripple" in the filtered signal. If the application requires very low ripple and constant DC output over a wide range of loading conditions, then active regulation is required to further reduce or eliminate this residual ripple.

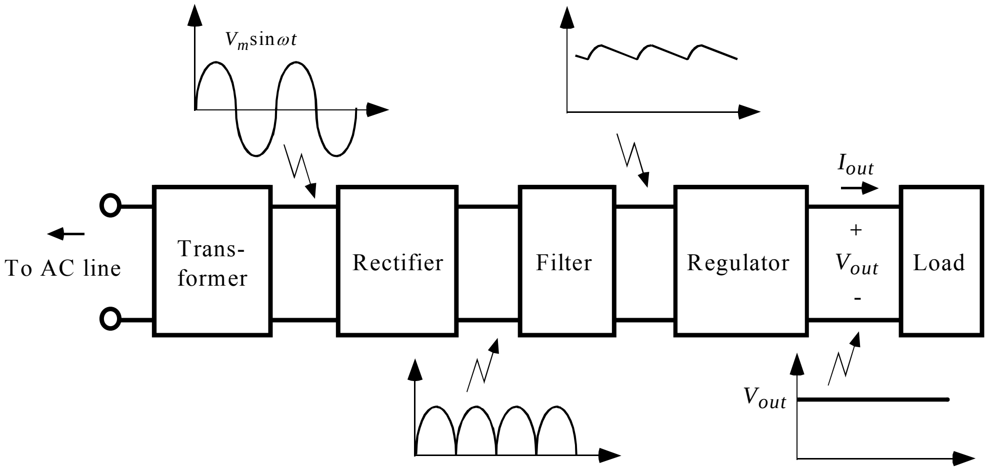


Figure 2-2 – Components of a typical linear power supply

We've already discussed diode rectifiers, so the transformer and rectifier combination should be easy to understand. Let's therefore start by considering the use of a shunt capacitor to "filter" the rectified sinusoid generated by a full-wave diode bridge rectifier. Figure 2-3 shows an unregulated supply with such a rectifier followed by a filtering capacitor C with a load resistance R connected at the output terminals. This is where your knowledge of RC time constants comes in: By adding a sufficiently large shunt capacitance at the output of the bridge rectifier, we can insure that the time-constant for discharging the capacitor through the load is long compared to the oscillation period. In other words, once charged, the voltage across the capacitor can not respond fast enough to track the time-varying voltage across the bridge rectifier, and hence remains approximately constant. We

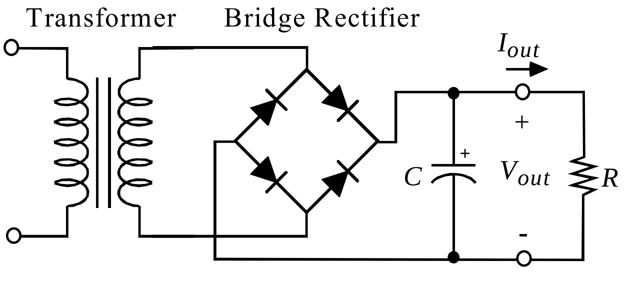


Figure 2-3 – Simple DC supply without active regulation.

---

[1] This is a simple but somewhat bulky and inefficient power-supply. So-called "switch-mode" or "switching" power supplies are more compact and efficient, but also more complicated.

say that the capacitance has “filtered out” the rapidly varying component of the rectified sinusoid to produce a constant DC voltage.

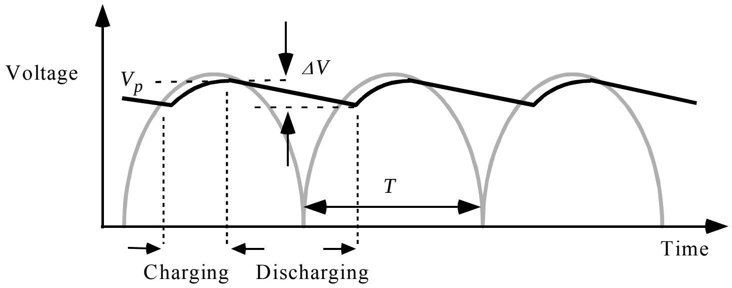


Figure 2-4 – Effect of the filtering capacitor on the rectified sinusoid under resistive loading conditions.

The action of the filter capacitor and load resistor combination is shown in Figure 2-4. As the rectified sinusoidal waveform begins to increase, the capacitor charges up and the voltage across it increases. On the downward portion of the rectified waveform, the capacitor begins to discharge into the load and the voltage across it decreases. The cycle then repeats, resulting in a periodic ripple of magnitude ΔV in the output waveform. To minimize this voltage “droop”, we must choose a sufficiently large capacitor so that the RC time constant is much greater than the oscillation period T. Clearly the choice of this capacitor is critically dependent on the load resistance, or maximum desired load current. As the load resistance goes down, the required capacitance goes up. Another equivalent way to understand this point is as follows: during the time period when the rectified sinusoid is low, the load current required to maintain a constant output voltage must come entirely from the stored charge on the capacitor. If the load requires a large current, a large amount of charge must be stored, requiring a large capacitor.

We can quantify these points in a simple way using the governing equation for a capacitor. During the discharging period the current is related to the capacitance and voltage droop by

$$I = C\frac{dV}{dt} \approx C\frac{\Delta V}{T} \quad \Rightarrow \quad \boxed{C = \frac{IT}{\Delta V} = \frac{V_{out}T}{R\Delta V}} \tag{2.1}$$

where we assumed that the voltage droop was relatively small so that the derivative could be approximated. This equation can be used to find the required filtering capacitance for a given load current and desired voltage droop. Clearly can never make ΔV zero with practical capacitors, and hence there is always some residual voltage droop. That brings us to a discussion of active regulator circuits.

Voltage Regulation

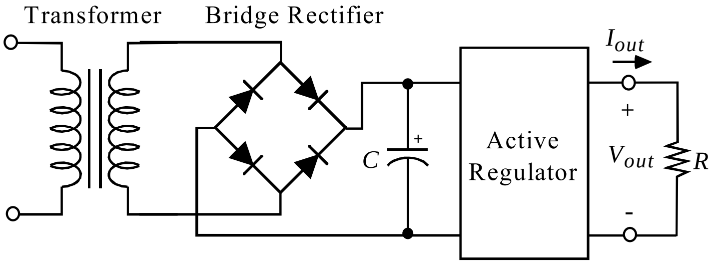


Figure 2-5 – Use of active regulators to minimize ripple or droop.

An active regulator circuit is inserted between the filtering capacitor and the load as shown in Figure 2-5. There are many different ways of achieving active regulation; we describe one simple scheme, outlined in Figure 2-6. The basic idea is to use feedback to control the amount of current going to the load. In the figure, a differential amplifier (such as an op-amp) provides the base current to a BJT transistor through which the load current will pass (hence the name “pass” transistor). The difference amplifier compares the output signal against a reference voltage (provided by a zener diode in this case) and controls the current through the pass transistor accordingly, so as to maintain an output signal $V_{out} \approx V_{ref}$. We can see this as follows: if the output voltage drops below V_{ref}, the transistor is driven harder to increase the load current. If the output voltage increases beyond V_{ref}, the base current is reduced and hence the load current is reduced to lower the output voltage. QED!

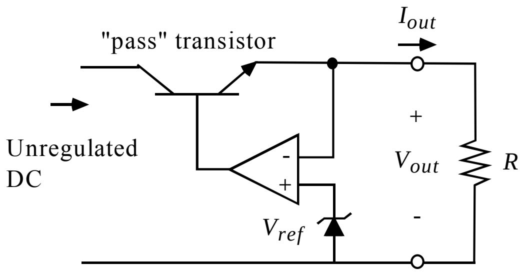


Figure 2-6 – A simple active regulator (conceptual schematic).

Using active regulation, very low ripple supplies can be made. Note that we have left out important details in the regulator schematic above, especially regarding the biasing of the difference amplifier and zener; such details increase the complexity of the circuit significantly. Practical regulator circuits may also include additional functionality such as ***current limiting***, in which case the output current is not allowed to exceed a certain threshold, or ***thermal shutdown*** in which case the output is shut off if the temperature of the pass transistor exceeds a certain threshold. Designers of regulator circuits may also go to great lengths to provide a very stable reference voltage. Nowadays it is rare to design your own regulator circuit from scratch since there are many useful ICs on the market that were designed specifically for this purpose. You will use two of them in this lab, the LM317 and LM337.

The kind of regulator we've just discussed is simple and easy to use, but is very inefficient. To operate correctly the input voltage must be substantially higher than the output voltage. For example, a regulated 5V output might use an unregulated 9V input, so at a load current of 1A there would be 4Watts dissipated in the regulator circuit. In addition to being very inefficient (5W out/9W in = 56% in this example), the regulator circuit will get very hot and require special provisions for heat removal. These problems get worse as the voltage drop across the regulator and/or the load current increase.

The final point of discussion concerns making "dual" DC supplies with both positive and negative output voltages. This is usually done using a "center-tapped" transformer, shown in Figure 2-7, where a third wire is attached to the middle of the secondary winding. If this terminal is taken as the common "ground" point in the secondary circuit, then the voltages taken at opposite ends of the winding will be positive or negative with respect to this point. We can then add separate positive and negative regulator circuits as shown. Many op-amp circuits have historically used dual-output power supplies of this type. It is possible to add additional circuitry to force the outputs to "track" each other precisely, so that the positive and negative supply voltages are exactly the same in magnitude; this is often used in precision instrumentation or high-quality audio applications. We will not construct this type of tracking power supply. Instead, we will make two independently adjustable positive and negative output voltages.

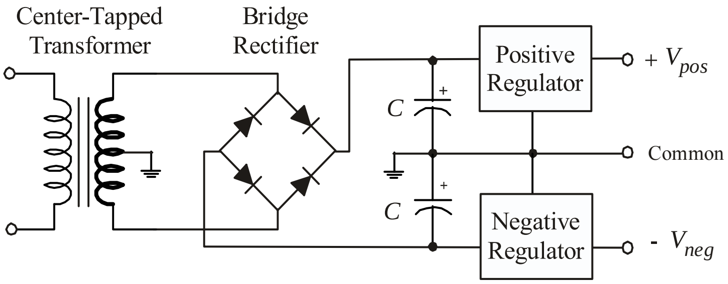


Figure 2-7 – Basic dual-supply system using a center-tapped transformer and two regulators. Note the polarity of the filtering capacitor in the negative supply circuit in the figure above.

In-Lab Procedure

Follow the instructions below CAREFULLY. Failure to do so could result in serious damage to the lab equipment, destruction of parts, and possible injury to you and your lab partner.

□ Each critical step begins with a check box like the one at the left. When you complete a step, check the associated box. Follow the instructions below and carefully document your results for inclusion in your lab report.

2.1 AC Power Transformer

You will be given a power transformer that is prewired to a 120V AC power cord with an in-line fuse, similar to the figure below. All 120V AC connections have been covered with heat-shrink tubing to protect you from accidentally touching the leads. Nevertheless, take care when handling these wires; do not yank or twist the connections. There should already be a fuse in the fuse-holder, and you have an extra one in your parts kit.

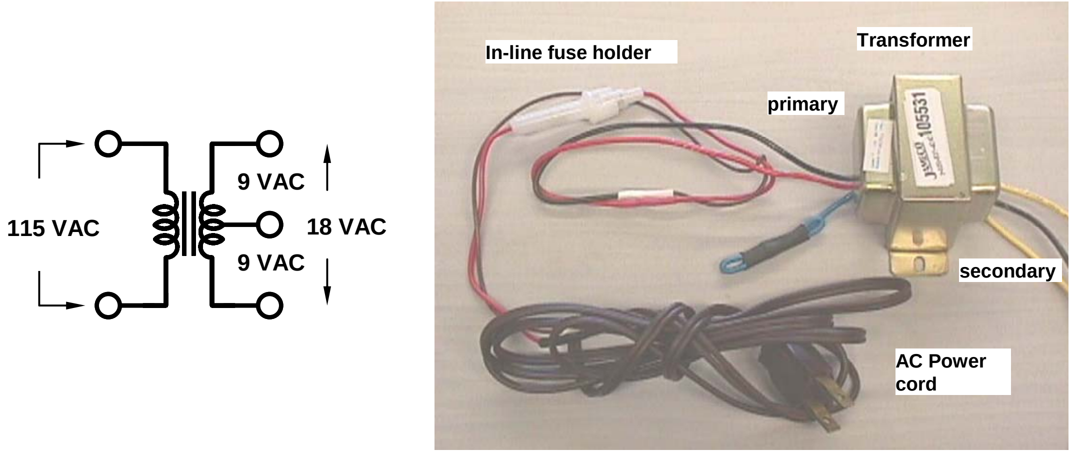


Figure 2-8 – (a) Transformer schematic and color code for leads.; (b) Power transformer with AC power cord and in-line fuse attached.

The transformer selected for this lab is specified for a 115 VAC input (primary) and an 18VAC center-tapped output (secondary), rated for >0.5 Amp in the secondary. It is important to remember that "VAC" always implies an rms voltage, so 18 VAC means something in excess of 25.5V peak-peak. In addition, transformers are always rate at the maximum current level, and due to the properties of the magnetic cores, the output voltage is usually somewhat higher at lower current levels.

□ Using the ¼″ 6/32 machine screws and nuts, firmly attach the power transformer assembly to the circuit board. Be sure to attach the earth ground to the case of the transformer.

2.2 Full-Wave Bridge Rectifier

We will use a full-wave diode bridge to rectify the AC signal. The diodes must be capable of sustaining the maximum expected current and voltage. We will use a Silicon 1N400x device rated at 1A and >100V. These devices are usually packaged as shown in Figure 2-9, with a white band marking the nearest lead as the cathode.

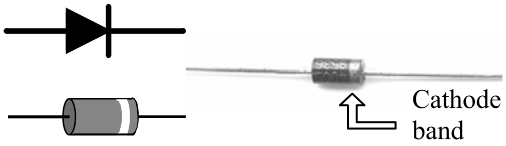


Figure 2-9 – Diode symbol and typical axial-lead package with a bandmarking the cathode. A photo of the rectifier diode used in this lab, 1N400x.

- ☐ Solder a bridge rectifier (Diodes D1-D4) on the circuit board. Carefully note the polarity of the diodes, and trim the leads as needed. It is essential to create good quality solder connections between the diodes; be sure to keep the soldering iron on the metal parts long enough so that the solder flows and does not bead. The resulting joint should have a smooth, shiny silver appearance, *not* a dull gray blob.
- ☐ Identify the secondary transformer leads and solder to the appropriate points of the diode bridge.
- ☐ Solder the center-tap lead on the secondary winding to an isolated flea clip on the board; ***this will be the common ground for the circuit***.
- ☐ Double check your wiring with a TA, then apply AC power. Record the rectified waveform in your LAB RECORD, taking care to note the peak amplitude in each case. Also note and record the oscillation period (in milliseconds) and mark on your graph. You may observe some distortion in the rectified sinusoid.

Before proceeding, disconnect the AC power!!

2.3 Filtering Capacitors

The next step is to "smooth" the rectified waveform to obtain a constant DC voltage. By adding a sufficiently large shunt capacitance at the output of the bridge rectifier, we can insure that the time-constant for discharging the capacitor through the load is long compared to the oscillation period.

The key observation here is that the loading conditions play a big role in determining the size of the filtering capacitor. If the load is small, we need a large capacitor to keep the RC time constant sufficiently large. Another way of thinking about this is that the capacitor must supply all the current to the load during the time that the rectified signal is low. If the load resistance is small, it will draw a significant current, which means that the capacitor must store a lot of charge, thus requiring a large capacitor.

Figure 2-10 – Electrolytic capacitor with axial leads. This particular capacitor is a 100μF with a maximum rated voltage of 50V. The lead on the right is indicated as "negative".

Large capacitors are usually of the electrolytic type as shown in Figure 2-10. These require special care when using, because they are designed for a specific polarization and maximum voltage. There is usually a marking on the case which indicates which lead is "positive" (+) or "negative" (-), as well as the capacitance value and maximum voltage. But please note:

> ***Mounting the capacitor backwards or exceeding the maximum voltage WILL cause the device to explode, sometimes dramatically and dangerously.***

In addition, large-value capacitors can store a lot of charge, so once they are charged up, they are capable of delivering an unpleasant electrostatic "zap". In this lab we will try to insure that the capacitors always have a resistive path to discharge themselves after the AC power has been removed, but as a general precaution:

> ***You should avoid touching the leads together on a large-value electrolytic if it has been charged!***

- ☐ With the AC disconnected, add a large electrolytic capacitor (Cp1 and Cn1) at the output of the bridge rectifier, with a 0.05Ω resistor (Rs) in series with C1 as shown below. ***Be sure to connect the electrolytics with the correct polarity***. Note that the sense resistor Rs is physically ***large***, despite the small value of resistance; it is designed specifically to handle more power (*i.e.* dissipate more heat) than a conventional ¼ Watt resistor. Solder the components in place ***after*** you have convinced yourself and the TA that you've got it right. As a general guideline, it is advisable to solder the capacitor in place with the polarity and value labels visible (facing up).

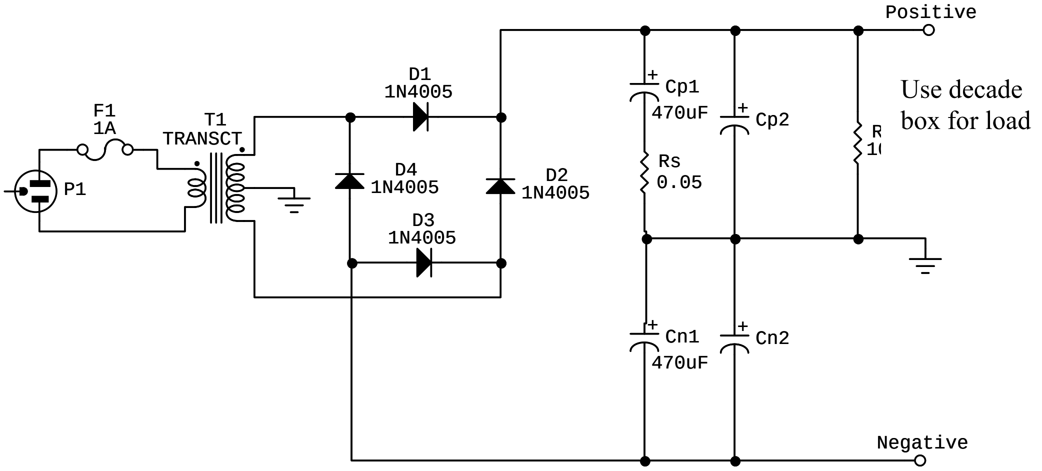


Figure 2-11 – Schematic for Step 3.

- ☐ Attach the power resistor decade box as the load impedance on the positive supply output as shown, and adjust to 555,555Ω. This setting will protect you initially against accidentally shorting out the supply circuit.
- ☐ Now plug in the circuit and record the output voltage with a multimeter in the LAB RECORD. Also examine the output waveform on the oscilloscope. Under nearly open circuit conditions (>500kΩ is essentially an open circuit in this context) the output voltage should be almost perfectly constant at the peak voltage of the rectified waveform.

This is because the capacitor charges quickly to this peak value, and the load current is not sufficient to discharge the capacitor significantly.

☐ Now, we want our power supply to provide a constant voltage for a wide range of load resistances, not just under open circuit conditions. Our objective is to supply 0.2 Amps at up to +12 Volts. What is the smallest load resistance that we can use without exceeding 0.2 A at +12 Volts? (Hint: use Ohms law!). Record this in your LAB RECORD. Then set the power resistor decade box to this value and record the output voltage waveform. Clearly we have some work to do in order for this supply to operate under these conditions!!

☐ Before going further, also record the voltage waveform across the "sense" resistor Rs. Using a small series resistance such as this gives a nice simple way of measuring or "sensing" the current flow in a certain path without seriously perturbing the circuit. What is the peak current flowing into the capacitor during the charging period? Mark this on your plot in the LAB RECORD.

Before proceeding, disconnect the AC power!!

☐ In order for our voltage regulator to work effectively, we need to make sure that the input voltage is above the desired output voltage (this is why the transformer was selected as having >18VAC output). We must select sufficient large capacitors to maintain a voltage droop of <1 Volt under maximum loading conditions. What is the minimum required capacitance that will maintain <1V ripple under maximum current (minimum load resistance) conditions? Record this in your LAB RECORD. Refer to the background section for how to compute this value.

☐ With the AC disconnected, solder in the extra capacitors as needed (labeled collectively as Cp2 and Cn2 in the schematic). You should have been given extra electrolytics for this purpose. It is okay to use MORE capacitance than that computed above, since that should reduce the droop even further (ultimately the amount of capacitance must be balanced against cost and space constraints when building power supplies).

☐ Power up and record the output waveforms under maximum current (minimum load resistance) conditions with the additional capacitors in place. Repeat this step for the negative supply output as well.

Before proceeding, disconnect the AC power!!

2.4 Adjustable Voltage Regulator

We will use a popular voltage regulator IC, the LM317 (positive voltage) and LM337 (negative voltage).

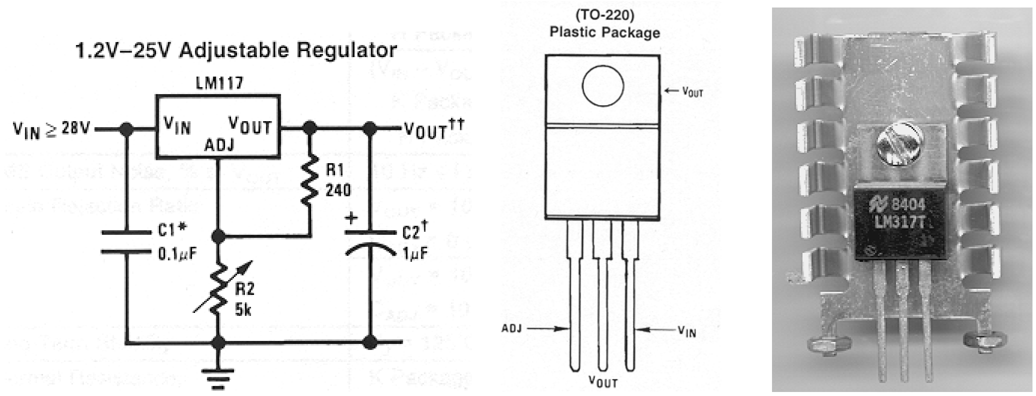


Figure 2-12 – Circuit connection for LM317 adjustable regulator, pin assignments in the TO-220 package, and a photo of the device attached to a heatsink.

Figure 2-12 shows a portion of the data sheet giving a typical connection for an adjustable positive supply using the LM317. The resistor divider provides feedback to the IC proportional to the output voltage, so that it can increase or decrease the current as needed. The chip is designed so that the output voltage is given by

$$V_{out} = 1.25\left(1 + \frac{R2}{R1}\right) + 0.0001R2 \qquad (2.2)$$

The capacitor at the Vin terminal (labeled C1 and C3 in our schematic) is recommended by the manufacturer if the device is more than 6 inches from the filter capacitors. The capacitance at the Vout terminal provides additional ripple rejection and rejection of transients, and is usually in the range of 1-100μF. In our circuit, this capacitor (labeled C2 and C4 in the schematic) was chosen as 10μF.

☐ Compute the resistor values required for +9 and +12 volt operation of the power supply and record in the LAB RECORD, assuming R1=240 Ohms.

☐ Before soldering the LM317 into the circuit, attach it to the small aluminum heatsink as shown in the figure above. There is some mounting hardware included in your kits for this purpose. The heatsink is especially important in components like this, which are dissipating significant amounts of power, all of which is converted to heat. Without proper heatsinking, such devices have a dramatically lower lifetime, scaling exponentially with the operating temperature. Do not use the mica insulating gasket or plastic washer when attaching the device to the heatsink; these are only used when it is important to electrically isolate the metal case of the device (at V_{out} potential) from the heatsink.

☐ With AC power disconnected, solder the regulator components (C1-C2, R1-R2, and the LM317) into the positive supply circuit as shown in the complete schematic. Carefully observe the pin diagram for the LM317 above: ***note that the center lead is not the ADJ terminal!!*** The heatsink has some tabs which can be inserted through the predrilled holes in the vectorboard, and you can bend the tabs back and use the leads of the LM317 to hold everything in place.

Resistor R2 is an adjustable trimmer potentiometer or “trimpot”, which can be adjusted from 0-5kΩ. A photo of a typical trimpot is shown in Figure 2-13 along with the schematic diagram for the leads.

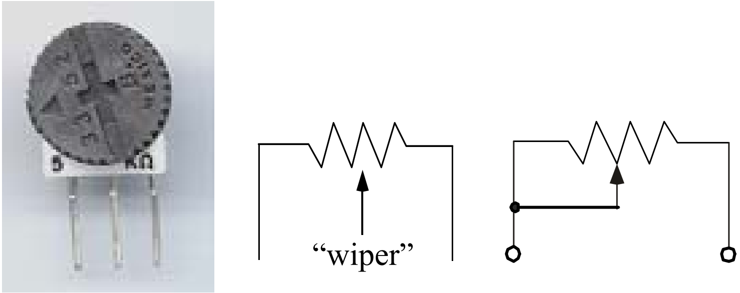


Figure 2-13 – Photo of trimpot and schematic symbol. Note: the resistance measured between the outer terminals is a constant resistance. The typical connection for a variable resistance is shown at right.

- ☐ Adjust the power resistor decade box to >100kΩ load and power up the circuit. Using a multimeter to monitor the DC output voltage, adjust the trimmer potentiometer to obtain the desired voltage level of +12 V.
- ☐ Now reduce the load resistance to the minimum allowable value (to give a maximum current of 0.2A) and record the output voltage waveform. You should no longer observe any large droop in the waveform, since the IC regulator is working to maintain a constant output voltage. Zoom in on the waveform using your oscilloscope (AC couple the input): you can still see some residual ripple, but it is very small; nevertheless, in high gain, high sensitivity circuits, such minor supply irregularities can cause major problems. More on that in Labs 3-4!
- ☐ Leave the circuit on for about 5 min., and then touch the heatsink on the LM317 (this is at +12V potential which is harmless). Is it warm?

Before proceeding, disconnect the AC power!!

- ☐ Repeat the above procedure for the negative supply regulator circuit using the LM337. You may wish to consult the data sheet for the LM337 for this step.

2.5 Finishing Touches

The next step is really not necessary, but is nevertheless useful: adding an LED indicator to signify that the circuit is “ON” and the output voltage is nonzero.

- ☐ With AC power disconnected, solder in the last two components, the red LED and its bias resistor R3. Be careful to observe the correct polarity on the LED as shown in the figure. You may wish to confirm this before soldering the component in place using the bench DC supply set to +12V.
- ☐ Repeat the last step using the green LED to indicate operation of the negative supply circuit.

- ☐ Power up the supply and confirm that the LED lights up and remains lit under assumed load conditions.

Disconnect the AC power.

The last step makes the circuit a little easier for us to use later on:

- ☐ There are three so-called "5-way" binding posts provided in the parts kit. Your board has been pre-dilled for attaching these posts. Screw them on at this time, using the RED post for the +12V output, the BLACK post for ground, and the GREEN post for the –12V output. These will provide convenient access to the supply outputs in later labs.
- ☐ At this stage you can add in the rubber feet to support the PC board.
- ☐ Demonstrate your working power supply to the TA, and have the TA certify your lab record at this time.

Disconnect the AC power.

Congratulations!
You have now completed Lab 2

Possible Improvements:

In practical prototyping work, it is smart practice to complete a circuit by placing it in an enclosure of some sort. This protects the circuit and also provides a convenient surface for attaching indicator lights, output terminals, fuses, switches, buttons, etc. There are a variety of inexpensive enclosures available for prototyping. However, it can also be a time consuming job to do correctly, which is why we did not attempt to do this here.

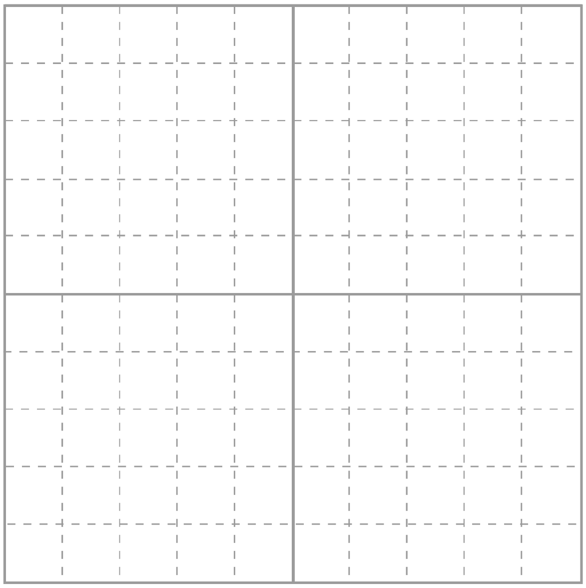
Lab Record

Lab Section: __________________ Names: ________________________________

____

Step 1-2: Transformer and bridge rectifier

Record rectified waveform and oscillation period (label axes and scales)



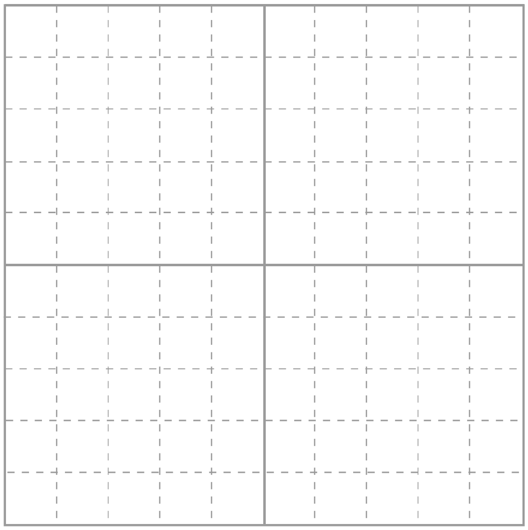
Step 3 – Filtering Capacitors

Unregulated open-circuit output voltage: ____________ Volts

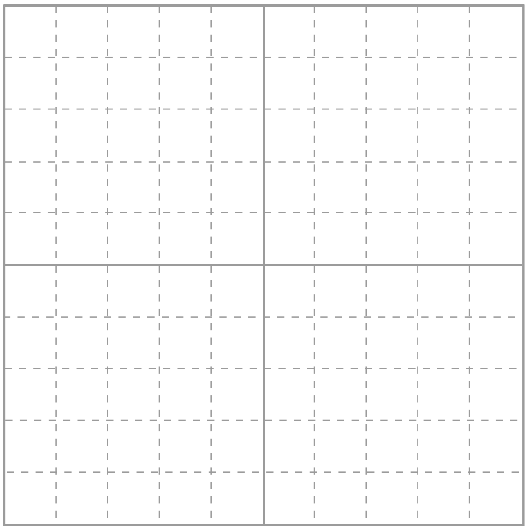
Minimum load for 0.2 Amp output current: __________ Ω

Record output waveform under above load condition, and also voltage across 0.05Ω sense resistor below. Label the plots with peak values and also axes/scale information:

Min. Load Output

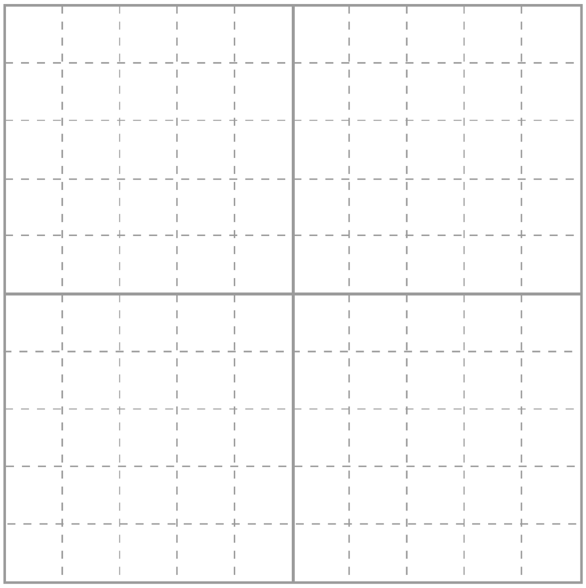


Charging Current



Capacitance to maintain <2V droop at above load: ____________ μF

Record output waveform under min load condition with additional filtering capacitors. Label the plot with peak values and also axes/scale information:



Step 4-5: Voltage Regulator and Indicator LED

Resistor value for +9 V output voltage: R2 = __________ Ω

Resistor value for +12V output voltage: R2 = __________ Ω

Record regulated output waveform under min load (max current) conditions with outputs set to +/- 12V. Label the plot with peak values and also axes/scale information:

Positive Output Negative Output

Voltage drop across LED: _____________ V

Forward current through LED: ___________ mA

LEDs illuminated on power-up? Yes [ ] No [ ]

TA Certification: _______________________ Date: ______________