Laboratory 1

Regulated DC 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 0.5 Amps (maximum) load current from a 120 V AC power outlet. This will be used to provide power to parts of the ultrasonic transceiver system that you will construct in later labs.

Single-output supply constructed in ECE 2C, Fall 2000

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
- Simple LED indicators
- Basic soldering techniques
Parts List

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<th>Part #</th>
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<td>6/32 nuts</td>
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Equipment List

- Bench Oscilloscope
- Bench multimeter
- Power Resistor Decade Box

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, Room 5106 (Hours 8:30-11:30AM, 1:30-4:30 PM, M-F). 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.).

Optional: simulate the regulated supply using Circuit Maker™ or MultiSim (circuit file available on the course web site).
Introduction to Linear Power Supply Design

Most common DC power supplies are designed as suggested in the figure below. First a transformer is used to “downconvert” the AC line voltage to a smaller peak voltage $V_m$, usually at least 2-3 Volts larger than the ultimately desired DC output. A diode circuit then rectifies the AC signal to generate a waveform with a predominant DC component. The rectified sinusoid is shown in the figure. 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 some active regulation is required to further reduce or eliminate this residual ripple.

You should have already discussed diode rectifiers in ECE 2A-B, so the transformer and rectifier combination is 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. The figure below 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 from ECE 2A-B 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 say that the capacitance has “filtered out” the rapidly varying component of the rectified sinusoid to produce a constant DC voltage.

The action of the filter capacitor and load resistor combination is shown in the figure above. As the rectified sinusoidal waveform begins to increase, the capacitor charges and the voltage across it begins to increase. 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 $\Delta V$ 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, which in turn requires 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

$$I = C \frac{dV}{dt} = C \frac{\Delta V}{T}$$

which is easily inverted to give

$$C = \frac{IT}{\Delta V} = \frac{V_{out}T}{R \Delta V}$$

This equation can be used to find the required filtering capacitance for a given load current and desired voltage droop. However, we clearly can not make $\Delta V$ zero with practical capacitors, and hence there is always some residual voltage droop. This is where active regulator circuits come into play.
An active regulator circuit is inserted between the filtering capacitor and the load as shown below.

Use of active regulators to minimize ripple or droop.

There are many different ways of achieving active regulation; we describe one simple scheme, outlined in the figure below. 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 biases 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!

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 custom design your own regulator circuit since there are many useful ICs on the market that were designed specifically for this purpose. You will meet two of them in this lab, the LM317 and LM337.
The final point of discussion concerns making DC supplies with both positive and negative output voltages. This is usually done using a “center-tapped” transformer, shown in the drawing below, 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.

Note the polarity of the filtering capacitor in the negative supply circuit in the figure above. 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 in Lab 1. Instead, we will make two independently adjustable positive and negative output voltages.

**In-Lab Procedure**

The complete schematic for the power supply is shown below. We will put this together in stages over two weeks (two lab periods).
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 step begin with a check box like the one at the left. When you complete a step, check the associated box. At the end of this document is a LAB RECORD in which you will record key observations and results from the experiment. When you are finished with the lab, you must demonstrate a working circuit and a completed lab record, and get this signed and certified by one of the lab TAs.

**Step 1 - AC Power Transformer**

The transformer selected for this lab is specified for a 115 VAC input (primary) and an 28VAC center-tapped output (secondary), rated for 1 Amp in the secondary. The color coding for the leads in shown in the figure below, along with the two possible connections for the different input voltages.

![Transformer schematic and color code for leads.](image)

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 heatshrink tubing to protect you from accidentally touching the leads. Nevertheless, take care when handling these wires; do not yank or twist the connections.

![Power transformer with AC power cord and in-line fuse attached.](image)
Using the ¼" 6/32 machine screws and nuts, firmly attach the power transformer assembly to the circuit board.

At this time, insert the fuse in the fuse-holder (if it is not already in place).

Note that there are a variety of power transformers available providing different output voltages, with and without the center-tap. In addition, many modern transformers include a center-tapped primary to allow for dual input voltages. Such transformers are quite common in commercial applications such as laptop power supplies and VCR battery chargers to allow for use in other countries where the wall-plug voltage is 220-230 VAC @ 50Hz, in addition to the American standard of 110-115 VAC @ 60 Hz.

**Step 2 – Full-Wave Bridge Rectifier**

We will use a full-wave diode bridge to rectify the 28V 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 the figure below, with a white band marking the nearest lead as the cathode.

![Diode symbol and typical axial package with a band near one lead marking the cathode. A photo of the rectifier diode used in this lab, 1N400x.](image)

Using the “flea” clips to hold the diodes, solder a bridge rectifier (Diodes D1-D4) on the circuit board, referring to the schematic for the correct connection. 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 be smooth, shiny, and silver, *not* a dull gray blob.

Identify the secondary transformer leads and solder to the appropriate points of the diode bridge on the backside of the board.

Solder the center-tap lead on the secondary winding (light green lead) 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!!*
Step 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 huge 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.

![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”.](image)

Large capacitors are usually of the electrolytic type as shown in the figure above. 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 quite a jolt of current. 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 470µF 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).
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 0.5 Amps at up to +12 Volts. What is the smallest load resistance that we can use without exceeding 0.5 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 about 1-2 Volts above the desired output voltage (this is why the transformer
was selected as having >24VAC output). Therefore we must select sufficient large capacitors to maintain a voltage droop of <2 Volts for our supply. What is the minimum required capacitance that will maintain <2V ripple under maximum current (minimum load resistance) conditions? Record this in your LAB RECORD. Refer to the tutorial 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!!

**Step 4 – Adjustable Voltage Regulator**

We will use a popular voltage regulator IC, the LM317 (positive voltage) and LM337 (negative voltage). A data sheet for this device is is available on-line on the class web site, and a copy should be in the lab.

The figure above 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

\[ V_{\text{out}} = 1.25 \left( 1 + \frac{R_2}{R_1} \right) + 0.0001R_2 \]

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 1-100\( \mu \text{F} \). In our circuit, this capacitor (labeled C2 and C4 in the schematic) was chosen as 10\( \mu \text{F} \).

- Compute the resistor values required for +9 and +12 volt operation of the power supply and record in the LAB RECORD, assuming \( R_1 \)=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, 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 used when it is important to electrically isolate the metal case of the device (at \( V_{\text{out}} \) 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 0-5k\( \Omega \). A photo of a typical trimpot is shown below, along with the schematic diagram for the leads.

Photo of trimpot and schematic symbol. Note: the resistance measured between the outer terminals is a constant resistance. 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 0.5A) 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.

Step 5 – LED indicator

The last 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.

LEDs are simple to use. Electrically they behave like a diode. Under forward bias, a typical LED will exhibit a turn on voltage of about 2V, and the rated brightness will be obtained at a current of 20-40mA. In our application, we will simply attach the LED at the output terminal of the supply. A bias resistor (R3) in series with the diode insures that the desired current will be obtained. We compute this resistor value as follows:

\[
R_3 = \frac{\text{output voltage} - \text{diode turn-on}}{\text{forward current}}
\]

For Vout = +12V, a resistor value of 470Ω gives slightly in excess of 20mA.

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.**

**Finishing Up**

- There are three so-called “5-way” binding posts provided in the parts kit. Your board has been predilled 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 1**

In the future:

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 in Lab 1.
Lab 1 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 0.5 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

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### Charging Current

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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: \( R_2 = \) \_________ \( \Omega \)

Resistor value for +12V output voltage: \( R_2 = \) \_________ \( \Omega \)

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:

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Voltage drop across LED: \( \) \_________ \( V \)

Forward current through LED: \( \) \_________ \( mA \)

LEDs illuminated on power-up? \( \) Yes [ ] \( \) No [ ]

TA Certification: \______________\____________ Date: \____________