Lab #3: Regulated DC Power Supply Using the LM317

Introduction

A simple DC power supply can be designed using only a transformer, a rectifier, and a filter capacitor. However, the average output voltage might not be stable because of line voltage fluctuations, and the output voltage ripple is significant unless a very large filter capacitor is used. Moreover, transformers are not available with a wide variety of secondary voltage options, especially in the very low voltages (e.g., 3.3 V, 1.8 V, or even lower) required by many modern electronic circuits. When a stable low voltage power supply with minimal ripple is required, the most common approach is to use a *voltage regulator* circuit. A wide variety of circuits are available for this task, ranging from zener diodes for very low-current applications to highly sophisticated integrated circuits and switching regulators. In this two-session lab exercise, you will design, assemble, and test a power supply based on a widely used integrated circuit regulator. Group assignments are listed at the end of this handout.

Theoretical Background

The three-terminal regulator is a relatively sophisticated integrated circuit that is widely used for producing steady DC voltages in modern electronic systems. Three-terminal regulators were first introduced in 1969 and have been under almost constant development since then [1]. The name of the device family reflects its packaging and ease of use. An example application is shown in Figure 1, which depicts a simple regulated power supply. The regulator is connected between the filter capacitor and the load. The device itself has only an input terminal, an output terminal, and a common reference terminal. Some three-terminal regulators provide only a fixed output voltage, but the LM317, which we will be applying in this lab exercise, can produce an adjustable output voltage if a few external components are added (R_1 and R_2 in Figure 1). A datasheet for the LM317 is available at the ECEG 350 Laboratory web page.

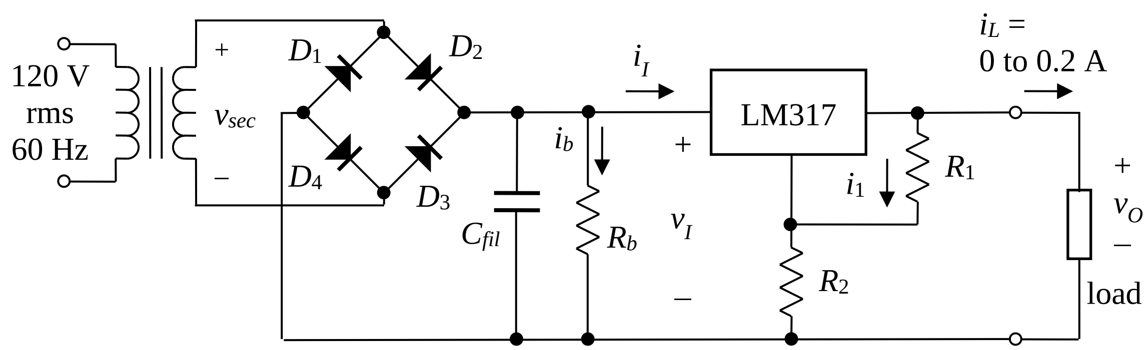

Figure 1. A basic power supply that employs an LM317 three-terminal voltage regulator to maintain the output voltage v_O close to a desired value. The value of filter capacitor C_{fil} must be chosen to maintain the input voltage v_I of the regulator above a certain threshold for all expected values of the load current i_L. A value of 120 Ω is recommended for R_1 if the LM317 is used [2]. Resistor R_b is a bleeder resistor; its purpose is to discharge filter capacitor C_{fil} when power is turned off.

Three-terminal regulators are very easy to use, hence their popularity. As shown in Figure 1, they are simply inserted between the filter capacitor and the load along with a few external components. Resistors R_1 and R_2 are always required since their values set the desired output voltage. The datasheet recommends a value of 240 Ω for R_1 [2], but for the LM317, it should be 120 Ω. This guarantees that the output current will be at least 10 mA, which is required for proper operation. (See the minimum load current specification in Sec. 7.7 of the datasheet.) The value of R_2 is determined using a formula given in the datasheet [2]. Additional capacitors and diodes are recommended as well in certain situations, but they should not be necessary for this circuit.

The selection of the value of C_{fil} requires a little thought. It must be large enough to maintain a sufficiently low ripple on the input voltage v_I of the regulator, but the ripple should not be so low that the capacitor is unnecessarily large. The voltage v_C across the capacitor is equal to the input voltage v_I of the regulator. It will have a ripple as it would in a basic power supply with no regulator because the capacitor is repeatedly charged and discharged as the transformer secondary voltage progresses through its sinusoidal cycle and the rectifier diodes turn on and off. The capacitor discharges into the regulator when the diodes are off. Although it is not stated explicitly in the datasheet, it implicitly recommends a minimum difference between v_I and v_O of 3 V. This is called the *dropout voltage*. In practice, the difference should be even higher than this to provide an operational cushion. Thus, the minimum capacitor voltage must be many volts greater than the desired output voltage v_O. The maximum capacitor voltage is equal to the available peak secondary voltage minus two rectifier diode voltage drops ($2V_F$). These two constraints together set the ripple voltage specification for v_C. That is one of the pieces of information needed to determine the minimum value of C_{fil}. All of this is discussed in more detail in the supplemental reading “Three-Terminal Linear Voltage Regulators,” which is available at the course Moodle site.

Another critical piece of information is the maximum current that flows out of the capacitor while it is discharging. That current includes i_I, which flows into the input terminal of the regulator, and the current i_b that flows through the bleeder resistor, although it might be possible to assume that $i_I >> i_b$. The input current i_I can be related to the load current i_L by remembering that KCL can be applied to entire regions of circuits, not just to circuit nodes. For the LM317 in Figure 1, application of KCL to the three terminals yields

$$i_I = i_{\mathrm{ADJ}} + i_1 + i_L,$$

where, as explained in Section 8.1 of the LM117/317 datasheet [2], current i_{ADJ} flows out of the reference terminal (the bottom terminal in Figure 1) and has a typical value of approximately 50 μA, although it can be as high as 100 μA. If the load current is substantial (100 mA or more), then $i_I \approx i_L$. The formula used to determine the values of resistors R_1 and R_2 is also explained in Section 8.1. Practical information regarding the location of resistor R_1 is given in Section 8.3.1.

References

[1] A. Bindra, “Three-Terminal Linear Regulator Evolution Continues Unabated,” *IEEE Power Electronics Magazine*, DOI: 10.1109/MPEL.2014.2361596, Dec. 2014, pp. 12–15.

[2] Texas Instruments, “LM117, LM317-N Wide Temperature Three-Pin Adjustable Regulator” datasheet, SNVS774Q, May 2004, rev. June 2020.

Preparation and Design Specifications

- During the first lab meeting, there will be an interactive demonstration of the characteristics of an unregulated power supply consisting of only a transformer, rectifier diodes, and a filter capacitor. This activity will cover the basic elements of power supply design up to but not including the regulator portion. Nevertheless, all of the guidelines covered in the demonstration will be applicable to the design of the regulated power supply. After the demonstration, you are strongly encouraged to read the "Design of Power Supplies with Linear Voltage Regulators" section of the supplemental reading "Three-Terminal Linear Voltage Regulators." That section reviews some of the basics of unregulated power supply design and then moves on to summarize the design of regulator circuits.

- Before moving on, read the following important warnings. They will save you much time and possible frustration.

  Warning #1: Do not attempt to measure both of the voltages v_{sec} and v_O in Figure 1 with the oscilloscope at the same time. If you try to do this, the ground leads will create a short across diode D_4 that will most likely lead to the destruction of diode D_1. You should trace the circuit connections in Figure 1 and understand how this can happen before proceeding.

  Warning #2: Electrolytic capacitors are polarized. Failure to pay attention to their polarity could result in their spectacular destruction, an unpleasant smell for everyone nearby, and possible personal injury. The marking on an electrolytic capacitor's package usually indicates its *negative* terminal. Look for a thick "–" sign, and interpret chevrons (angled lines) as arrows.

- Design a power supply with an LM317 three-terminal regulator like the one shown in Figure 1 using one of the supplied transformer boxes. Consult the LM317 datasheet for details regarding the selection of external resistor and capacitor values. The power supply must meet the following specifications and guidelines:

  1. DC output voltage: approximately 9 V
  2. Maximum load current demand: 150 mA
  3. Current i_1 through resistor R_1 should be roughly 10 mA to meet the minimum load current specification of the LM317, which is necessary for it to operate properly.
  4. Average power dissipation of LM317: less than approx. 2.0 W at maximum load current (The goal is to avoid using a heatsink.)
  5. Rectifier diode type: 1N4001 or 1N4007 (data sheet available on lab page)
  6. Bleeder resistance R_b: should discharge the filter capacitor to 5% of its maximum voltage within 10 sec after the power supply is turned off but without loading down the rectifier significantly (i.e., its current should add as little as possible to $i_{I\max}$).
  7. All diodes and resistors must be capable of dissipating the maximum expected time average power. This requirement includes any resistors used to simulate the load R_L for testing purposes. Make sure that any estimated values are reasonable for the worst cases expected. Apply a ×2 safety factor. You may combine resistors in series or parallel only for the purpose of meeting power dissipation requirements.

8. The filter capacitor C_{fil} must be large enough for reliable operation at maximum load current but not excessively large. You may combine capacitors in series and/or parallel only if single units with sufficient capacitance are not available. Keep in mind that the tolerance of electrolytic capacitors is typically 20–40% and that electrolytic capacitors are bulky and relatively expensive. An excessively complicated filter capacitor network will be viewed unfavorably!
9. For safety reasons, the transformer is enclosed in a box with a power cord and a circuit breaker. As shown in Figure 2, the three jacks on the box are connected to the secondary winding. The two outer jacks connect to the ends of the winding, and the center jack connects to a center tap. You will need to determine which pair of jacks to use by measuring the voltages between them and by considering the maximum and minimum filter capacitor voltages that you will need. Note that the output waveform of the transformer secondary might not be perfectly sinusoidal due to the presence of power line noise and/or harmonics in the local voltage supply.

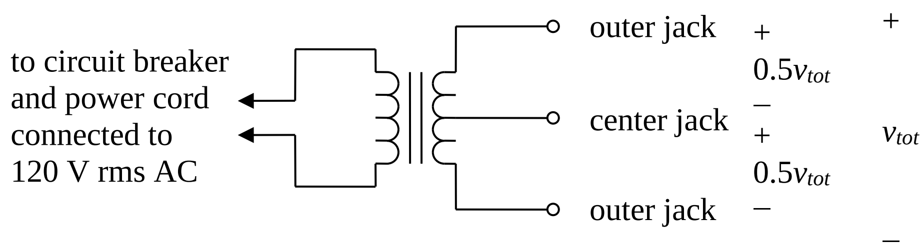

Figure 2. Connections to transformer inside its enclosure.

<u>Experimental Procedure</u>

- After the design process for the regulated power supply has been completed, assemble it (except for the transformer, of course) on a breadboard.

  As explained in Sec. 8.3.1 of the LM117/317 datasheet (you should read it), the upper end of resistor R_1 should have a very short and low-resistance connection to the output terminal of the regulator. If the resistance along that path is more than a few tenths of an ohm, the load regulation can be adversely affected at high output current levels. This effect (called stray resistance) is very likely to be present in your circuit because all of it will be assembled on a breadboard. The stray resistance of breadboard contacts can be quite high. There is not much that we can do about that, but we will observe the impact that it has on regulator circuit performance.

- Devise a way to test whether the circuit is working correctly at full rated output current. A successful test includes ensuring that none of the components overheats and that the filter capacitor discharges within the specified period through the bleeder resistor when the circuit is turned off. The equivalent load resistance should be infinite or a very large value for the bleeder resistor test. (Do you know why?) Under normal operation, the output voltage should have only a tiny amount of ripple (maybe 10–20 mV or less at full output current) with no large dips.

- Display the capacitor voltage (v_I) and output voltage (v_O) waveforms simultaneously on the oscilloscope, and confirm that your power supply meets all specifications and design goals. Troubleshoot any problems. The ripple voltage might be so low that you will need to trigger the oscilloscope with the v_I waveform. You will probably have to switch to a sensitive vertical scale (small V/div setting) and move the 0 V level off of the screen to see the details of the output voltage waveform. Use the manual cursors to determine the peak output voltage and ripple voltage. Use the "BW Limit" feature to minimize the noise from WVBU.

- Capture an image of the oscilloscope screen simultaneously displaying the output voltage and capacitor voltage waveforms at full rated output current. Choose appropriate vertical and horizontal scale settings so that the key features of each waveform are clearly evident. Use the cursors to indicate important voltages and/or time instances.

- With the load drawing the maximum specified current (~150 mA) from the power supply, use your observations of the capacitor voltage and output voltage waveforms to calculate the line regulation of the circuit. Compare the measured value to the specified value on the LM317 datasheet. Record all of your observations and calculations; they will be presented during the post-lab meeting. Before attempting your measurements, it will be helpful to read the "Line Regulation" section and the "Measuring Load and Line Regulation" section of the supplemental reading "Three-Terminal Linear Voltage Regulators."

- Measure and record the DC output voltage obtained when the supply provides 0%, 25%, 50%, 75%, and 100% of the maximum rated load current. You will need to modify your load to make these measurements. Make sure that any resistors that you use do not dissipate more power than they are rated to handle; otherwise, your measurements might be affected. You might wish to set up separate loads on your breadboard to allow for faster, easier, and repeatable switching between them for your tests and later demonstration. Use the bench-top voltmeter to obtain measurements with several digits of accuracy. You should find that the measured values trend slightly downward in value as the average load current increases. Use the data to calculate the load regulation, and compare the calculated value to the specified value on the datasheet. The measured value will probably be much worse than the specified value. (Do you know why?) Record all of your observations and calculations; they will be presented during the post-lab meeting. For helpful guidance, read the "Load Regulation" section of the supplemental reading "Three-Terminal Linear Voltage Regulators."

- Schedule a 30-minute post-lab meeting with me at a mutually agreed time before the deadline posted on the Laboratory page at the course web site. The following guidelines apply:

    - Read these guidelines and the "Post-Lab Meeting" section below well in advance of the meeting. You will need to prepare a set of visual aids.
    - **All tables must be formatted according to the guidelines posted on the Laboratory page at the course web site. Data tables must be prepared using software.**
    - **All equations, variables, and other mathematical content must be formatted according to the posted guidelines as well.**
    - All group members must be present.
    - The meeting will take place in the Maker-E if Dana 307 is not available at the scheduled time.

- Meetings will be scheduled in the order that requests are received. The order might be determined by random assignment. Meetings will not be scheduled during a lecture, lab, or recitation section for another course or during important work, athletic, performance, or similar commitments. Please notify me of time conflicts.
- Meetings will not be rescheduled if the first one reveals circuit problems, wiring failures, errors in the test procedure, or a lack of preparation.
- Deadline extensions will generally be approved for confirmed illnesses or other extenuating circumstances.

- Compile the visual aids that your group intends to use into a single PDF document and **submit it via the course Moodle site** before the post-lab meeting begins. Use a file name of the form

  “LName1_LName2_LName3_Lab3_fa24.pdf,”

  where “LName1,” “LName2," and “LName3” are the group members’ last names. Include the underscore (_) characters. Add “LName4” if your group has four members. The file size must be less than 5 MB. Keep a copy of your documentation if you wish to use it to prepare for the next exam or need it for future reference.

Post-Lab Meeting

The group must address the first set of prompts listed below, and then each group member must respond to one of the individual prompts in the next set (a different prompt for each person) and possibly answer a few follow-up questions. The following guidelines apply:

- Each person will have a time limit of **five minutes** in which to respond.
- You may assign the individual prompts to group members before the meeting.
- Each response must be supported by high-quality visual aids prepared by the respondent, including a properly labeled circuit diagram (or diagrams). **All tables, equations, variables, and other mathematical content must be formatted according to the guidelines** posted on the Laboratory page at the course web site. **Data tables must be prepared using software.** Graphics such as circuit diagrams may be prepared by hand, but they must be very neat and legible.
- The line and load regulation tables will be assessed at the group level.
- Visual aids must be complete enough for understanding but not so information-packed that they are overwhelming or create visual clutter that detracts from clarity.
- The physical circuit layout and connections to equipment should be well planned so that group members can switch between demonstrations quickly.

The group prompts are:

1. Display an oscilloscope image of the output voltage waveform at full rated current at the rated voltage along with the capacitor voltage waveform. The ripple on both waveforms must be evident. The displayed waveforms should clearly indicate that the power supply is working properly.
2. Demonstrate that the filter capacitor voltage drops to under 5% of its maximum value within 10 sec under no-load ($R_L \rightarrow \infty$) conditions after turning off the AC supply.
3. Explain how the filter capacitor’s value was determined.

The individual prompts are listed below. A two-person group must address Prompts #2 and #3:

1. [Not used in a 2-person group:] Explain how the value of the bleeder resistor R_b was determined. Also explain how its presence was accounted for (or why its effect was deemed insignificant) when the value of the filter capacitor was determined.
2. Demonstrate how the line regulation was determined from measurements, and explain how the corresponding specification in the datasheet was interpreted to compare it to the measured value. The line regulation data and results must be presented in a well-organized and properly formatted table with caption. (The table quality will be assessed and scored at the group level.)
3. Demonstrate how the load regulation was determined from measurements, and explain how the corresponding specification in the datasheet was interpreted to compare it to the measured value. The load regulation data and results must be presented in a well-organized and properly formatted table with caption. (The table quality will be assessed and scored at the group level.)
4. [Four-person group only:] Explain how you ensured that the maximum average power dissipation of the regulator IC did not exceed 2.0 W at full rated output current.

At the end of the demonstration, if there is time, your circuit will be used to supply power to a speaker/amplifier connected to a music source.

There could be some general discussion of your design process and measurements, the performance characteristics of your circuit, how you handled any uncertainties, and other related topics. If you made unusual choices, you must be prepared to defend them. A good demo must have excellent oral and visual components that are well integrated. It will be challenging to achieve a perfect score.

Lab Scoring Criteria

Each group member will receive a score based on the following criteria quantized at the indicated point values. The first three criteria constitute a group base score; that is, each group member will receive the same score for those criteria. The remaining criteria will be assessed independently and will be determined by that person’s contribution to the post-lab meeting. The rubrics posted on the Laboratory page at the course web site will guide the assignment of scores.

0, 10, 20, 30, 35, 40 pts	Functional circuit w/appropriate component values (group)
0, 2, 5, 8, 10 pts	Quality of load regulation data/results table (group)
0, 2, 5, 8, 10 pts	Quality of line regulation data/results table (group)
0, 8, 15, 23, 30 pts	Quality of response to prompt (indiv.)
0, 2, 5, 8, 10 pts	Quality and effectiveness of supporting visual aids (indiv.)

If the meeting is completed after the deadline, a 10% score deduction will be applied for every 24 hours or portion thereof that it is late (not including weekend days) unless extenuating circumstance apply. No credit for the individual criteria will be given four or more days after the deadline; however, up to 60 pts will be assigned to each member of the group for the group criteria if at least one member demonstrates a functional circuit within a week of the deadline.

Group Assignments

The randomly generated groups for this lab exercise are listed below:

1:00 pm Section:
Amsili-Giffen-Ottman
Griffin-Lennon-Murphy
Pudasaini-Theosmy

3:00 pm Section:
Kennedy-Kucic-Paccione
LaMontagne-Strausser-Wickert
Khasabo-Page-Philogene