Experiment No. 3.
Power Supplies and Linear Regulators

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All electronic systems which operate on DC voltages (+5 V, ±12 V, etc.) and are plugged to the AC (120 V, 60 Hz) system require a power supply. This includes all audio components (CD player, tape player, receiver, etc.) and most home/office electronic units (computers, printers, alarm clocks, microwave ovens, and dishwashers/fridges/washing machines if they have microprocessor controls). A power supply schematic is shown in Figure 1. The 120 V AC voltage is first stepped down to ~12 V AC using a transformer, then passes by a diode bridge rectifier and a low-pass "filtering" capacitor. The resulting DC voltage has a ripple of around $\pm10\%$ V_p (for example 12V $\pm$ 1 V).

The main focus of Experiment No. 3 is on the input section of the power supply, mainly the transformer, diode rectifier and the low-pass capacitor. The relevant equations for a full-wave or half-wave bridge rectifier are given in the course notes. Notice that these equations are accurate to $\pm25\%$ since they are derived from very simple assumptions. They are intended to give a conservative estimate of the output voltage ripple, the peak diode current and the peak inverse voltage.
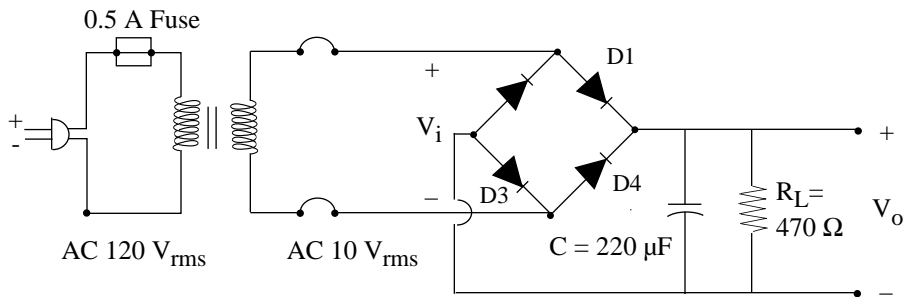

Figure 1: A full-wave bridge rectifier.

Dual (Positive and Negative) Output Power Supplies:

In order to get a dual output power supply, a center-tap transformer <u>must</u> be used. The center tap is usually connected to ground. Relative to the center tap, one of the output transformer lines is at a positive voltage and the other is at a negative voltage. A full-wave rectifier delivering dual-output voltages is shown below:
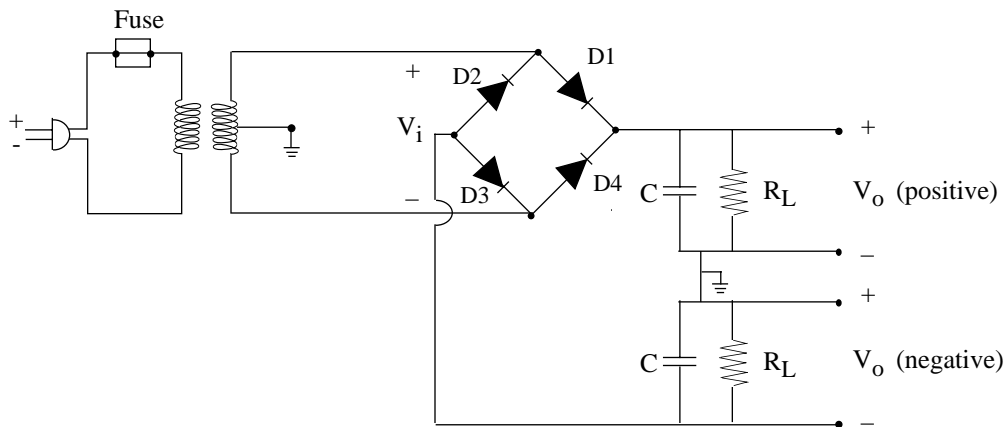
A full-wave single-output rectifier can also be obtained using a center-tap transformer as indicated below:
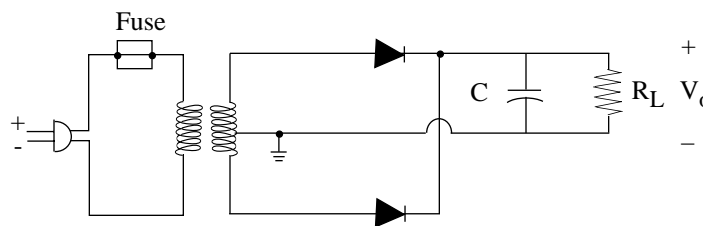
There is basically no difference in Vpk, V_R, and Id between this topology and the four-diode bridge, except that this topology requires a center-tap transformer and results in a peak-inverse voltage across the diodes of (2 Vpk – V_D).

Linear Regulators:

The full-wave bridge rectifier has terrible voltage regulation! This means that if R_L decreases by a factor of 2 (thus the output current is doubled), the output voltage ripple doubles! Also, if the input voltage (called line voltage) changes by $\pm$10% (which is quite typical in 120 V AC systems), then the output DC voltage also changes by $\pm$10%! Therefore, a power supply composed of only a transformer, a bridge rectifier and a capacitor is quite bad for high performance applications, and linear regulators must be used to ensure very low voltage ripple and excellent load and line voltage regulation.

Linear (or series) regulated power supplies were introduced many years ago and are still used extensively today. The basic design technique consists of placing a control element in series with the rectifier and load device. Figure 2 shows a simplified schematic of a series regulated supply with the series element depicted as a variable resistor. Feedback control circuits continuously monitor the output and adjust the series resistance to maintain a constant output voltage. Because the variable resistance (series element) of Fig. 2 is actually one or more power transistor operating in the linear (class A) mode, supplies with this type of regulator are often called *linear* power supplies.
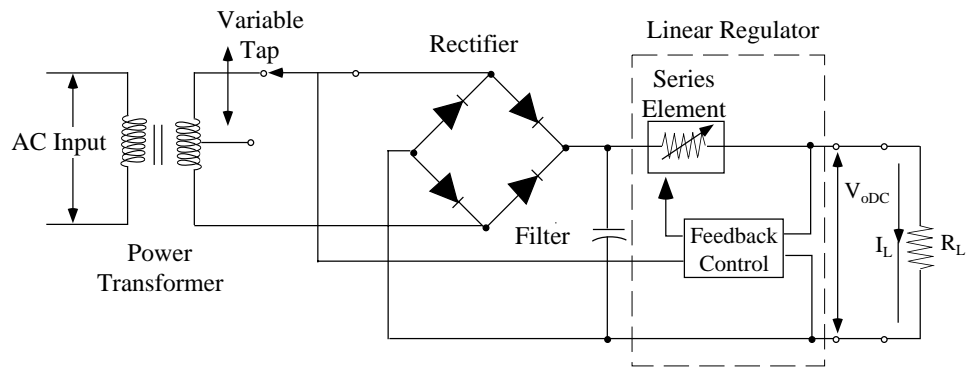
Figure 2: The Agilent E3631A power supply.

In terms of performance, linear regulated supplies have a very precise regulating properties and respond quickly to variations of the line and load. Hence, their line and load regulation and transient recovery time are superior to supplies using other regulation techniques (such as switching mode power supplies). These supplies also exhibit low ripple and noise, are tolerant of ambient temperature changes, and with their circuit simplicity, have a high reliability.

Series regulated power supply are not efficient and in some cases dissipate a lot of power. Let us take the example of a bridge rectifier designed to give 15 V $\pm$ 1 V DC and connected to a (series) linear regulator with an output regulated voltage between 5 and 12 V. If the output voltage is 12 V, then the voltage drop across the series regulator is 3 V. For an output current of 1 A, the output power is 12 W (P_O), the power consumed by the regulator is 3 W and the bridge rectifier therefore delivers 15 W (P_{in}). Thus the regulator efficiency (P_O/P_{in}) is 12 W/15 W = 80% which is quite good. However, if the output voltage is 5 V, the series regulator voltage drop is 10 V and the power consumed by the regulator is 10 W. This results in a poor regular efficiency (P_O/P_{in}) of 5 W/15 W = 33%! For high output currents/powers a poor efficiency means that a huge amount of power is consumed in the linear regulator!

One way to solve this problem is to always make sure that the rectified bridge voltage is only a few volts (1-2 V) above the required output voltage, thereby resulting in a low power dissipation in the regulator (and high efficiency).

For a high-power variable voltage power supply such as the Agilent E3631A, the feedback controls the transformer tap so as to change the input DC voltage to the regulator. This is expensive and requires a DC motor or SCR switches to move the tap, but results in a very efficient power supply.

Multiple Output Power Supplies:

If several output voltages are needed such as +5, +12 and +24 V, then it is best to use a multiple-tapped transformer with 3 different rectifiers and regulators as shown in Fig. 3a.
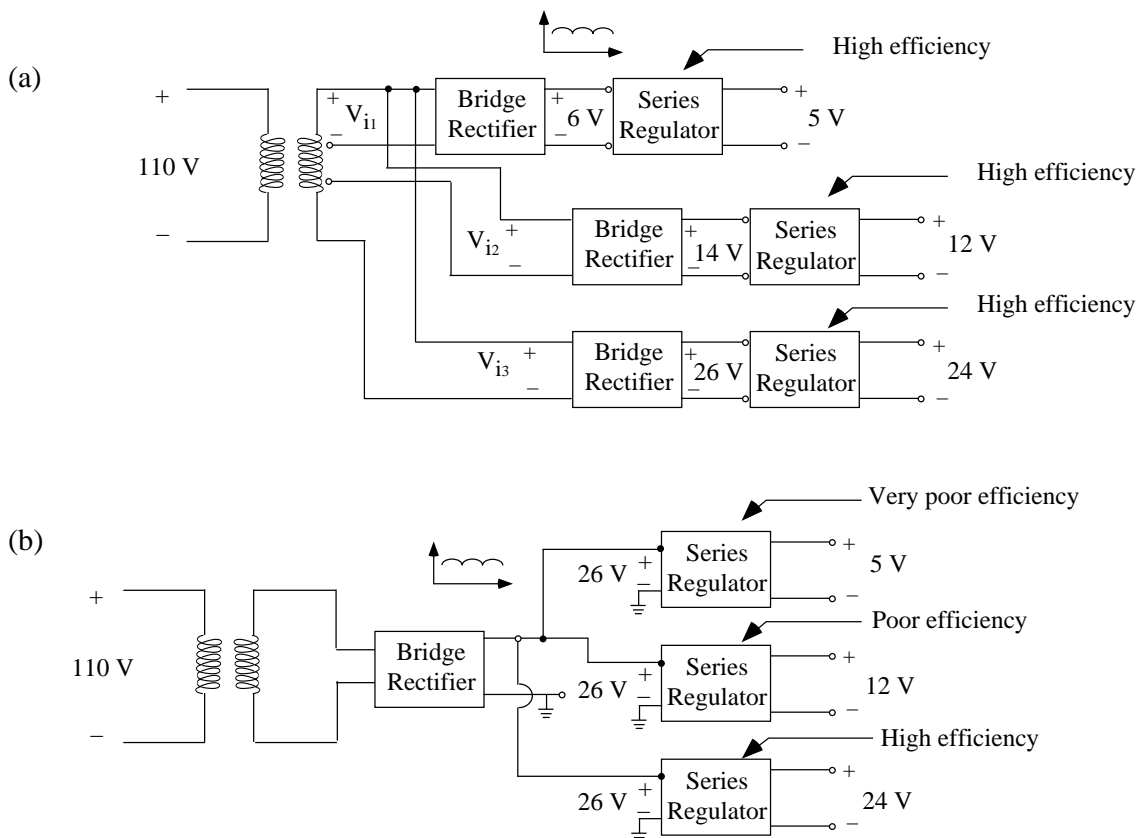

Figure 3: An efficient multiple output power supply with multiple-tapped transformer (a) and a simple but very inefficient implementation (b).

This is much more power efficient than using a simple transformer/rectifier and three regulators (Fig. 3b).

Linear Regulator Specs:

Linear regulators specifications are easy to understand and their performance is summarized in a few specifications:

Regulated Output Voltage $\equiv V_o$ ($\sim$1 V to V_{line} - 2 V)

Output Voltage Ripple $\equiv V_R$ (mV levels)

Line Regulation $\equiv \dfrac{\Delta V_o}{\Delta V_{in}}$ $\dfrac{\text{Change in output voltage}}{\text{Change in input voltage}}$ (<mV/V)

Load Regulation $\equiv \dfrac{\Delta V_o}{\Delta I_L}$ $\dfrac{\text{Change in output voltage}}{\text{Change in output current}}$ ($\sim$mV/A)

Short Circuit Current $\equiv I_{SC}$ (10 mA to 10 A)

The data sheet of the LM 105/205/305/376 linear regulator family is in the Appendix.

Switching Power Supplies:

As seen above, linear regulators are not efficient especially if a large range of output voltages are needed. For high power systems a switching power supply is used. The theory of these supplies are beyond this course but it suffices to say that they are very efficient (85-95%) and can deliver large amounts of power (50-1000 W). However, they do *not* offer excellent line and load regulation, low ripple and low noise as linear power supplies. For this reason, all analog/instrumentation/audio systems use linear regulators and all digital/computer/printer systems use switching power supplies.

Diodes & Bridge Rectifiers

Half-Wave Rectifier

Full-Wave Rectifier
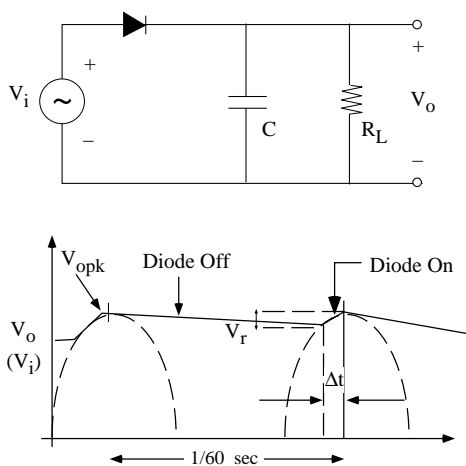
$$V_{opk} = V_{ipk} - V_D \qquad (V_D \approx 0.7\,V)$$

$$V_{oav} = V_{opk} - \frac{V_r}{2}$$

$$V_r = \frac{V_{opk}}{fR_LC} \qquad (f = 60\,Hz)$$

$$\omega\,\Delta t = \sqrt{\frac{2V_r}{V_{opk}}} \qquad (\omega = 2\pi f)$$

$$I_L = V_{opk}/R_L$$

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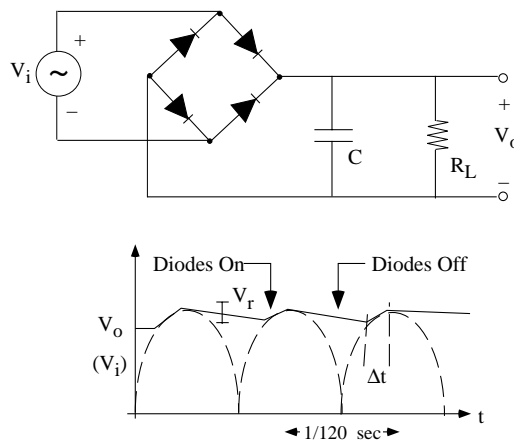$$I_{D(av)} = (I_L)\left(1 + \pi\sqrt{\frac{2V_{opk}}{V_r}}\right)$$

$$I_{D(pk)} = (I_L)\left(1 + 2\pi\sqrt{\frac{2V_{opk}}{V_r}}\right)$$

$$I_{C(av)} = (I_L)\left(\pi\sqrt{\frac{2V_{opk}}{V_r}}\right)$$

$$I_{C(pk)} = (I_L)\left(2\pi\sqrt{\frac{2V_{opk}}{V_r}}\right)$$

$$I_{D(av)} = (I_L)\left(1 + \pi\sqrt{\frac{V_{opk}}{2V_r}}\right)$$

$$I_{D(pk)} = (I_L)\left(1 + 2\pi\sqrt{\frac{V_{opk}}{2V_r}}\right)$$

$$I_{C(av)} = (I_L)\left(\pi\sqrt{\frac{V_{opk}}{2V_r}}\right)$$

$$I_{C(pk)} = (I_L)\left(2\pi\sqrt{\frac{V_{opk}}{2V_r}}\right)$$

Experiment No. 3.
Diodes and Bridge Rectifiers

Goal: To learn about diodes and to use a diode bridge to build a 14V full-wave rectifying DC power supply.

❑ Read this experiment and answer the pre-lab questions.

Equipment:
- Agilent E3631A Triple output DC power supply
- Agilent 33120A Function Generator
- Agilent 34401A Multimeter
- Agilent 54645A Oscilloscope

1.0 Diode Test Circuit:

1. Set the Agilent E3631A power supply to give a maximum current of 0.6A for the +6V supply. This is important so as not to burn the diode while testing it.

2. Connect the MUR 105 silicon rectifier diode as follows:
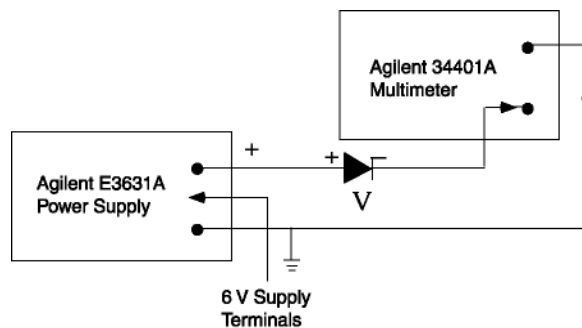
3. ❑ Measure the diode current for V = 0.3, 0.4, 0.5, 0.7, 0.8, 0.9, 1.0, 1.2 and 1.3 up to a diode current of 0.5A.

Determine the diode voltage for Id = 1mA, 10 mA and 100 mA.

2.0 Full-wave Bridge Rectifier with a Single Output:

1. ❑ Measure R_L and the 0.5 Ω resistor accurately using the multimeter.

   ❑ Measure C using the capacitance meter in the lab.

2. Connect the full-wave bridge rectifier as shown below and make sure that the diode polarity and the capacitor polarity are correct. There is a small (0.5 Ω) resistor in series with the 220 µF capacitor. This resistor is needed so as to measure the current in the 220 µF capacitor ($I_C = V_C/R$).

TURN OFF THE POWER SUPPLY AND THE MULTIMETER. DISCONNECT ALL CABLES FROM THESE UNITS AND RETURN THE CABLES TO THEIR ORIGINAL PLACE. THIS IS VERY IMPORTANT SO AS NOT TO HAVE GROUND LOOPS AND BURN THE FUSE! YOU WILL NOT USE THESE UNITS AGAIN.

ALSO, ALWAYS OPERATE WITH A SINGLE COAX TO BANANA-PLUG OSCILLOSCOPE CABLE!
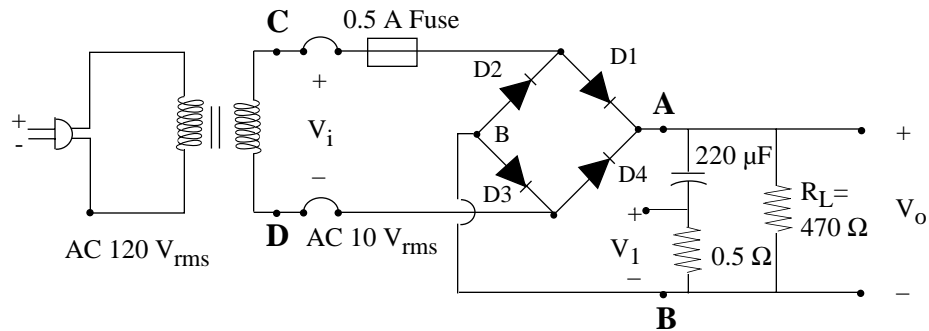
After you have checked the circuit, connect the transformer to the 120 V AC wall outlet. If there is a short-circuit, the fuse will blow and $V_i = 0$!

a. ❑ Draw the circuit in your lab notebook.

b. ❑ Measure V_{ippk} and V_{irms} using the scope. At this time, connect the oscilloscope ground to point D. It should be 10-11 V_{rms}.

c. ❑ Measure the spectrum of V_i in dB (f_o, $3f_o$ and $5f_o$). You will notice that the waveform is not perfectly sinusoidal due to the cheapie wall tranformer. The magnetic case is saturating at high voltages and distorting the transformer output signal (V_i)!

BE CAREFUL WHEN YOU ARE DOING VOLTAGE MEASUREMENTS ACROSS THE DIODE BRIDGE ACROSS R_L, ETC. MAKE SURE THAT THE SCOPE GROUND IS NOW CONNECTED TO NODE B!

3. ❑ Remove the capacitor and measure V_o. Make sure that you have a full-wave rectified voltage. (Do not worry if you see a distorted sinewave.) Measure V_{opk} and determine the diode voltage drop (per diode).

4. a. ❑ Connect the capacitor to the circuit and measure Vopk, Vo(av) and V_R (the ripple voltage) and compare with your pre-lab calculations. Plot V_o.

   ❑ Measure the frequency of the output voltage ripple.

   ❑ From the output voltage waveform, measure the charging and discharging time of the capacitor.

   ❑ From the output voltage waveform, measure the slope ($\Delta V/\Delta T$) of the discharge portion at the *center* of the linear portion. As discussed in class, this results in the discharge capacitor current ($I = C \Delta V/\Delta T$) which is equal to the load current.

   b. ❑ Measure V_o in the frequency domain and write the fundamental harmonics in dB (120, 240, 360 and 480 Hz).

5. On the scope, measure the voltage (V_1) across the 0.5 Ω resistor. This measurement results in the charging and discharging capacitor current ($I = V_1/R$, $R = 0.5$ Ω). Again, the discharge capacitor current is equal to the load current.

   ❑ Draw accurately the current waveform ($I = V_1/R$) on your lab notebook and label the peak positive (charging) current and its duration, the average negative (discharge)

current and its duration (the average discharge current is found at the center of the linear portion of V_1). Label the charging and discharging periods of the capacitor.

3.0 Half-Wave Power Supply With a Single Output:

Assume that one of the diodes blew up and became an open circuit (D2 for example). the circuit becomes a half-wave rectifier.

❏ Take D2 <u>out</u> of the circuit now. Draw the circuit in your lab notebook.

❏ Repeat parts 3, 4 and 5 of section #2.

Experiment No. 3.
Diodes and Bridge Rectifiers

Pre-Lab Assignment

1. For the full-wave bridge rectifier with C = 220 µF, R_L = 470 Ω and V_i = 10 Vrms:

   a. Calculate the ripple frequency, V_{pk}, V_R, I_L, $I_{D(av)}$ and $I_{D(pk)}$.

   b. Calculate the time in msec (per period) that the diode(s) is turned on.

   c. Plot the current in the 220 µF capacitor for one period.

2. Repeat (1) but for a full-wave bridge rectifier when one of the diodes is blown. This is equivalent to a half-wave rectifer but with two diodes in series. Therefore, in this <u>special case</u>, you should take into account the voltage drop of two diodes and $V_{opk} = V_{ipk} - 2\,V_D$ in the half-wave rectifier equations.

3. Regulators are <u>essential</u> for low output ripple voltages and this problem will show why! For the full-wave rectifier with R_L = 470 Ω,

   a. Choose C to result in V_R = 100 mV and V_R = 10 mV.

   b. Calculate $I_{D(av)}$ and $I_{D(pk)}$ in each case.

   c. Calculate the time in msec or µsec (per period) that the diode(s) is turned on.

      You will find that in order to get a low ripple voltage from a bridge rectifier, the time each diode is "on" is very short and the peak diode current is extremely large! This is why most bridge rectifiers have a ripple voltage around ±10% and are followed by linear regulators.

4. Calculate the efficiencies of the multiple output linear regulators of Fig. 3a and 3b if each output is delivering the same current I (the answer is independent of I).

5. Assume that the Agilent E3631A power supply with a variable output from 0–25 V does <u>not</u> have a controlled-tap transformer, and V= 26 V (fixed) after the bridge rectifier/low-pass filter.

   a. Calculate the efficiencies of the linear regulator when the output voltage is set at 2 V, then at 25 V, and delivers 1 A to a load in both cases.

   b. What is the power consumed by the linear regulator in each case?

   c. Repeat a and b above with a controlled tap transformer (take a 1 V drop across the regulator).

Experiment No. 3
Diodes and Bridge Rectifiers

Lab Report

1. Report all your measured values in the full-wave bridge rectifier C = 220 μF, R_L = 470 Ω (voltages and capacitor current times, input voltage, component values, etc.) and compare with calculations done using your <u>measured</u> V_{irms} (or V_{ippk}), and assuming an ideal diode model (V_D = 0.7 V). Put the measured data and calculations in table form. Comment on the discrepancies, especially for the peak current in the capacitor.

2. Report all your measured values in the half-wave bridge rectifier C = 220 μF, R_L = 470 Ω (voltages and capacitor current). Put the measured data and calculations in table form. Compare with calculations and comment on the discrepancies.

3. The load current can be obtained in three separate methods:

    – Using $V_{o\ (av)}/R_L = I_{L(av)}$
    – Using the slope of the discharge portion of V_o (I = C ΔV/ΔT).
    – Using V_1/R in the middle of discharge period of the capacitor.

    Using your measurements and the exact values of R_L, C and the 0.5 Ω resistor, determine $I_{L(av)}$ using the above methods and comment on any discrepancies. You will find that the "slope" method is the least accurate. Why?

4. A high performance regulated power supply for audio systems with the following outputs is needed:

    Power Supply #1:

    +5 V (I_{max} = 500 mA):   Microprocessor Circuitry

    ±12 V (I_{max} = 1 A):   Analog Small-Signal Audio Circuitry

    Power Supply #2:

    ±24 V (I_{max} = 6 A):   Output Audio Power Amplifier to drive the speakers

    a. First of all, ideally how much audio power can this system give into an 8 Ω speaker without clipping? The #2 supply can deliver a ± 24 V max. and ± 6A current max. Therefore, the output of the power amplifier can go to ± 24 V (assume no voltage drop in the output amplifier).

    b. Design the power supplies (#1 and #2) for high efficiency. You can use a multiple-tap transformer and several rectifiers/regulators. Choose appropriate capacitors for each supply. The unregulated output of each rectifier should have a ±15% (or 30% total) ripple voltage <u>at peak current load</u>.

    c. Assume that the voltage drop is 0.5 V across the 5 V linear regulator and 1 V across each of the 12 V and 24 V linear regulators. Calculate the overall regulator efficiency.