Power Supply calculations

ECE 2100

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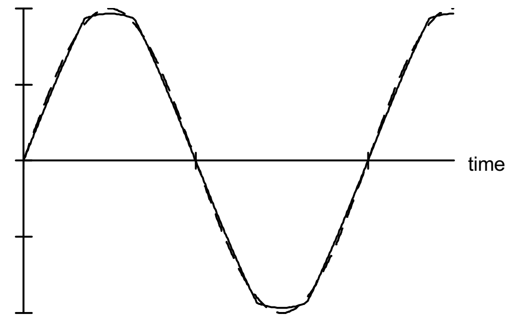
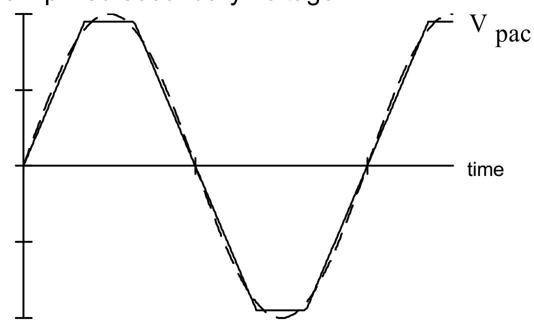
You can make a simple power supply from a small transformer, a rectifier circuit, and a filter capacitor. These types of power supplies are discussed in section 3.7, p.179 of your textbook. Unfortunately this section fails to consider the characteristics of small transformers and it turns out that the transformer characteristics are very important. If you don't consider them in your analysis then your analysis is pure fiction and useless for design purposes.

secondary voltage



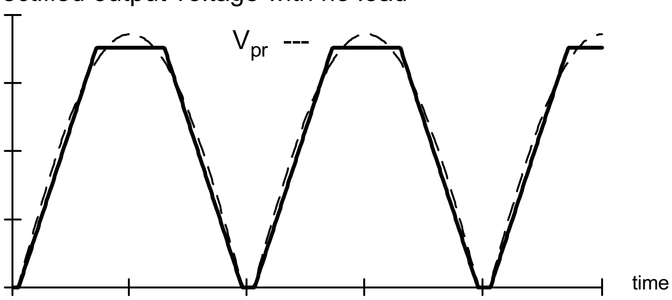
First, The iron cores of these small transformers aren't very linear, resulting in a secondary voltage that isn't really a sine wave. Usually the secondary voltage looks more like the top waveform at right than a sine wave. It usually has a flattened top and rather straight sides. For our analysis, we'll simplify It further to the straight-line approximation shown at right.

simplified secondary voltage

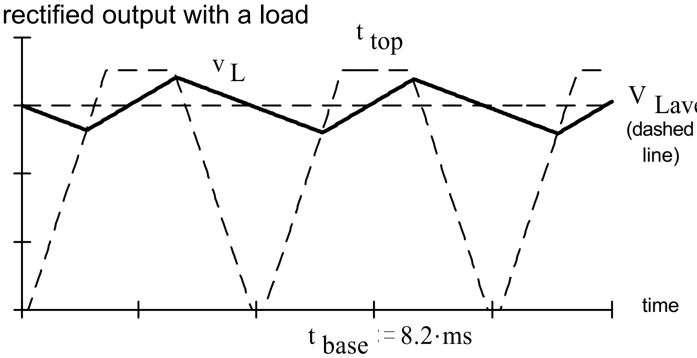


Second, the windings in these transformers are made with real wires, and not particularly thick ones. That means the windings have resistances that cannot be neglected, especially in a rectified and filtered circuit where the transformer current flows in pulses which are much higher than the average current. Because the actual current pulses are much higher than the average current, the voltage drop across the winding resistance is also much higher than you'd expect to see with a constant current. Also, since the transformer secondary voltage is specified by the manufacturer at full current, the no-load voltage will be higher than specified.

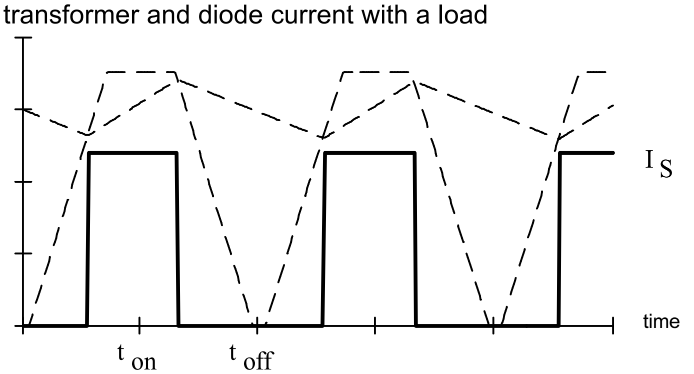
rectified output voltage with no load



rectified output with a load



transformer and diode current with a load



Design & Analysis method

1. Specify the required load current (I_L).
2. Select possible transformer and rectifier configuration.
3. Measure transformer & diodes you intend to use and/or make assumptions for unmeasured parameters.

   For the best results you should measure these parts, but since that isn't always possible, I've also given some ways to estimate the needed parameters.
4. perform some weird calculations to find the average voltage at the load (V_{Lave}).
5. If V_{Lave} isn't adequate, go back to step two and repeat with different parts or rectifier configuration.
6. If V_{Lave} is adequate, find or specify the allowable peak-to-peak ripple at the load (V_r) and, find the filter capacitor needed.

Design & Analysis

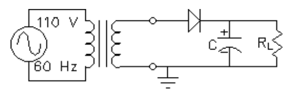
1. Specify the required load current (I_L). This come from the requirements of the load.

2. Select possible transformer and rectifier configuration.

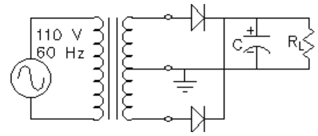
   Although a transformer with an RMS voltage rating of 12V should give rectified DC of more than 16V, after all the losses in a real power supply, it's usually good for a 12V DC supply.

   Diodes should be rated for the same current as the transformer

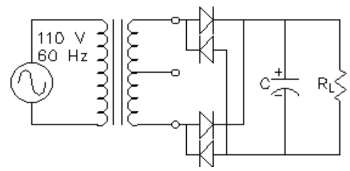
Transformer specs

half wave:


$V_{RMS} \geq V_L$ $I_{rated} > 1.3 I_L$

full wave:


$V_{RMS} \geq 2V_L$ $I_{rated} \geq 0.7 I_L$

bridge: full wave:


$V_{RMS} \geq 2V_L$ $I_{rated} \geq I_L$

These recommendations are a rough guide only

3. Measure transformer & diodes you intend to use and/or make assumptions for unmeasured parameters.

Take some transformer measurements (all secondary) | **Or assume these values in the absence of data**

RMS voltage, no load: VnL_{rms} — VnL_{rms} = Rated secondary rms voltage + 2V

RMS voltage, with load (R_1): VL_{rms} — VL_{rms} = Rated secondary rms voltage

(Select an R_L so that the secondary current is approximately the rated secondary current.)

Load resistor used: R_L — $R_L = \dfrac{\text{Rated secondary rms voltage}}{\text{Rated secondary rms current}}$

Winding resistance:

$$R_w = \frac{VnL_{rms} - VL_{rms}}{VL_{rms}} \cdot R_L$$

Don't try to measure winding resistance with an ohmmeter, that won't include the effects of the primary winding or the core. Instead, actually hook the transformer up to 110V, and measure the secondary voltage with and without a load.

Use a scope to view the loaded secondary voltage and measure the following

Peak voltage of the AC wave: V_{pac} — $V_{pac} = 13.8 \cdot VL_{rms.}$

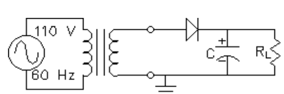
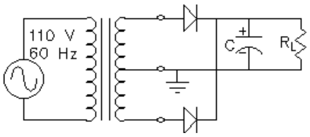
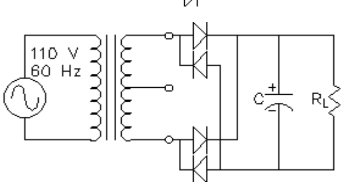
Waveform measurements: (see drawing on first page) t_{top}, t_{base} — $t_{top} := 2.4 \cdot ms$, $t_{base} := 8.2 \cdot ms$

Take some diode measurements | **Or assume these values in the absence of data**

Forward voltage drop at expected current: V_{fd} — $V_{fd} := 0.9 \cdot V$

Diode resistance: r_d — $r_d = \dfrac{50 \cdot mV}{I_L}$

Use the measurements to determine a important numbers for the circuit

Rectification circuit	Source resistance	Peak of rectified waveform:	Period of rectified waveform:
half wave: 	$R_s = R_w + r_d$	$V_{pr} = V_{pac} - V_{fd}$	$T_r := \frac{1}{60} \cdot s$
full wave: 	$R_s = R_w + r_d$ Make R_w measurements on the half winding	$V_{pr} = V_{pac} - V_{fd}$	$T_r := \frac{1}{120} \cdot s$
bridge: full wave: 	$R_s = R_w + 2 \cdot r_d$	$V_{pr} = V_{pac} - 2 \cdot V_{fd}$	$T_r := \frac{1}{120} \cdot s$

Notice that if this is the same transformer it will have double the output voltage and double the winding resistance of the configuration above.

Calculations

4. perform some weird calculations to find the average voltage at the load (V_{Lave}).

The "a" term of a quadratic equation: $a := \frac{t_{base} - t_{top}}{2 \cdot V_{pr}}$

The average voltage at the load: $V_{Lave} = V_{pr} - \frac{-t_{top} + \sqrt{t_{top}^2 + 4 \cdot a \cdot I_L \cdot R_s \cdot T_r}}{2 \cdot a}$

5. If V_{Lave} isn't adequate, go back to step two and repeat with different parts or rectifier configuration.

6. If V_{Lave} is adequate, find or specify the allowable peak-to-peak ripple at the load (V_r) and, find the filter capacitor needed.

Peak-to-peak ripple: V_r Absolute minimum voltage will be: $V_{Lave} - \frac{V_r}{2}$

Conduction time: $t_{on} = t_{base} - \frac{V_{Lave}}{V_{pr}} \cdot (t_{base} - t_{top})$ Time when diodes conduct & capacitor charges

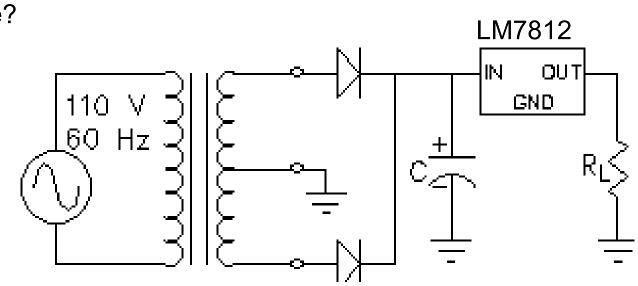
Non-conduction time: $t_{off} = T_r - t_{on}$ Diodes off, capacitor discharges

Capacitor value: $C = \frac{I_L \cdot t_{off}}{V_r}$ Interestingly, although the capacitor is absolutely necessary to make the calculations above work, it's value isn't all that important to anything but the ripple voltage.

The best way to deal with this mess is to program it into a computer, either a spreadsheet, or a math program would do well. You could even program it using a regular programming language, but that probably isn't worth the trouble. I'd suggest that you enter these calculations in a spreadsheet or math program now, as you have some homework problems and a lab that require these. You can test your work on the following example.

Example Power Supply calculations

1. I have a transformer rated at 25.2 Vrms CT @ 1A. I would like to use this to supply an LM7812 three terminal voltage regulator with 800 mA. This regulator requires at least 14.6 V at its input to provide a regulated 12 V output. Will it work? That is, will the transformer be adequate?



1. Specify the required load current (I_L). $I_L := 800 \cdot mA$

2. Select possible transformer and rectifier configuration:

First I want to see if it will work with the full wave rectifier shown at right, so I need the transformer characteristics for half the winding (between the center tap, CT, and one side).

3. Measure transformer & diodes you intend to use and/or make assumptions for unmeasured parameters.

V_{pac} $V_{pac} := 21 \cdot V$

t_{top} $t_{top} := 2.4 \cdot ms$

t_{base} $t_{base} := 8.2 \cdot ms$

VnL_{rms} $VnL_{rms} := 15.248 \cdot V$

VL_{rms} $VL_{rms} := 13.035 \cdot V$ $R_L := 10 \cdot \Omega$ $R_w := \frac{VnL_{rms} - VL_{rms}}{VL_{rms}} \cdot R_L$ $R_w = 1.698 \cdot \Omega$

diode, 1N4002: $r_d := 0.1 \cdot \Omega$ $V_{fd} := 0.9 \cdot V$

Source resistance: $R_s := R_w + r_d$ $R_s = 1.798 \cdot \Omega$

Peak of rectified waveform: $V_{pr} := V_{pac} - V_{fd}$ $V_{pr} = 20.1 \cdot V$

Period of rectified waveform: $T_r := \frac{1}{120} \cdot s$

4. perform some weird calculations to find the average voltage at the load (V_{Lave}).

$a := \frac{t_{base} - t_{top}}{2 \cdot V_{pr}}$ $\quad V_{Lave} := V_{pr} - \frac{-t_{top} + \sqrt{t_{top}^2 + 4 \cdot a \cdot I_L \cdot R_s \cdot T_r}}{2 \cdot a}$ $\quad V_{Lave} = 16.079 \cdot V$ > 14.6V, OK

6. If V_{Lave} is adequate, find or specify the allowable peak-to-peak ripple at the load (V_r) and, find the filter capacitor needed.

$V_r := 2 \cdot (V_{Lave} - 14.6 \cdot V)$ $\quad V_r = 2.96 \cdot V$

Conduction time: $t_{on} := t_{base} - \frac{V_{Lave}}{V_{pr}} \cdot (t_{base} - t_{top})$ $\quad t_{on} = 3.56 \cdot ms$

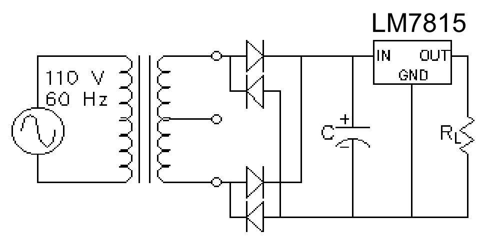
Non-conduction time: $t_{off} := T_r - t_{on}$ $\quad t_{off} = 4.773 \cdot ms$

Capacitor value: $C := \frac{I_L \cdot t_{off}}{V_r}$ $\quad C = 1291 \cdot \mu F$ Need a 1300 μF cap. Use 2600 μF for 2x margin of safety (these calculations aren't all that good).

2. The same configuration won't work to power a LM7815, 15 V regulator, which needs a minimum input of 17.7 V, at least not at 800 mA. I find that for 390 mA I'd need a 4200μF cap, or for 430 mA, a 20000μF cap & that's about the limit. Let's try for 800mA with a bridge rectifier configuration and use double the transformer V_{pac} and R_w.

1. Specify $I_L := 800 \cdot mA$ $\quad V_{min} := 17.7 \cdot V$

2. Select possible transformer and rectifier configuration:



3. Measure transformer & diodes you intend to use and/or make assumptions for unmeasured parameters.

$V_{pac} := 42 \cdot V$ $\quad R_w := 3.4 \cdot \Omega$ double previous values

Source resistance
bridge: $R_s := R_w + 2 \cdot r_d$ $\quad R_s = 3.6 \cdot \Omega$

Peak of rectified waveform:
$V_{pr} := V_{pac} - 2 \cdot V_{fd}$ $\quad V_{pr} = 40.2 \cdot V$

Period of rectified waveform:
$T_r := \frac{1}{120} \cdot s$

4. perform some weird calculations to find the average voltage at the load (V_{Lave}).

$a := \frac{t_{base} - t_{top}}{2 \cdot V_{pr}}$ $\quad V_{Lave} := V_{pr} - \frac{-t_{top} + \sqrt{t_{top}^2 + 4 \cdot a \cdot I_L \cdot R_s \cdot T_r}}{2 \cdot a}$ $\quad V_{Lave} = 32.149 \cdot V$, $V_{min} = 17.7 \cdot V$ OK

6. If V_{Lave} is adequate, find or specify the allowable peak-to-peak ripple at the load (V_r) and, find the filter capacitor needed.

$V_r := 2 \cdot (V_{Lave} - V_{min})$ $\quad V_r = 28.9 \cdot V$ Which is ridiculous, since $V_{pr} = 40.2 \cdot V$ try $V_r := 16 \cdot V$

Conduction time: $t_{on} := t_{base} - \frac{V_{Lave}}{V_{pr}} \cdot (t_{base} - t_{top})$ $\quad t_{on} = 3.562 \cdot ms$

Non-conduction time: $t_{off} := T_r - t_{on}$ $\quad t_{off} = 4.772 \cdot ms$

Capacitor value: $C := \frac{I_L \cdot t_{off}}{V_r}$ $\quad C = 239 \cdot \mu F$ Need a 240 μF cap. Use 480 μF for 2x margin of safety.