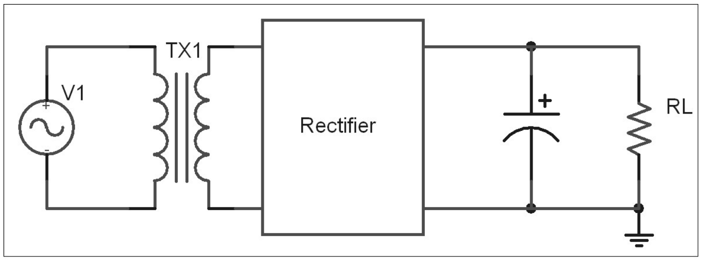
Power Supply Filtering

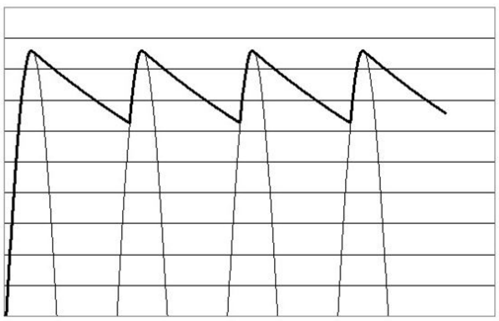
In a previous course, you were introduced to the concept of filtering -- removing unwanted frequency components from a compound signal. With DC power supplies, we want the DC component, which has a frequency of zero. Therefore, we want to create a Low Pass Filter to remove all components from our rectified signal other than zero, or DC. We could use a series resistor and a capacitor to ground, but it turns out that the following configuration of a Low Pass Filter is much more effective for our circuit, because of the characteristics of the diode.



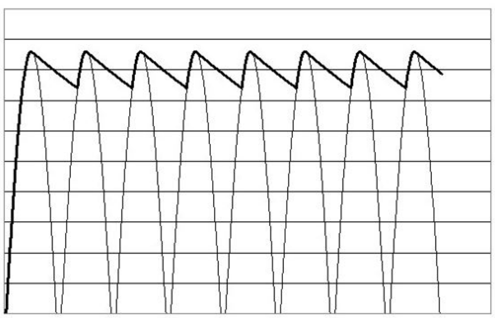
This arrangement uses the circuit load, R_L, as the resistor in the filter, so no power is dissipated to anything but the load.

However, the even greater improvement over a standard series LPF is the way the capacitor is charged by the diode or diodes in the rectifier.

The capacitor can be quickly charged through the very low internal resistance of the forward biased diode or diodes, raising the capacitor voltage to very nearly the peak voltage of the rectifier. However, when the rectifier voltage would normally drop, the diodes become reverse biased, and no current drains back. This means that the only current drain from the capacitor is through the load, which has a much higher resistance than the forward biased diode or diodes had, so the voltage does not drop very quickly. We achieve the following result for a half-wave rectifier:



For a full-wave rectifier, the result is even better (no surprise, given that the frequency is double, and therefore further from zero):



In each of these, the rising side practically follows the rectified input up; then, the capacitor begins its slow discharge through the load, only to be overtaken by the next rising side.

Mathematically, this is a difficult signal to analyze, as the point at which it switches from a falling exponential curve to a rising sinusoid changes with the rate of decay of the exponential. An attempt to solve for this produces a situation in which the time cannot be isolated -- it's always either in a sine expression or in an exponent. Consequently, the best we can do to predict the characteristics of these signals is to form an approximation.

Ripple

The tops of these waveforms look like waves on water, so their amplitude is referred to as "Ripple Voltage". This is typically measured in peak-to-peak volts.

The ripple amplitude is affected by the following three variables:

1. Discharge time, which is the period of the rectifier frequency. The shorter the period, the less ripple appears.
2. Size of the capacitor. A large capacitor stores more charge, so the bigger the capacitor, the less ripple appears.

3. The load current. The bigger the current, the more charge is drained, so the smaller the load resistance (i.e.) the more current, the more ripple appears.

Putting these together, we arrive at the following relationship:

$$Vr = \frac{I_L T}{C}$$, in $V_{p\text{-}p}$

The problem that arises is that the current is dependent on the voltage, which is changing in a way that can't be mathematically isolated.

$$I_L = \frac{V_L}{R_L}$$, but V_L can't be definitely determined.

For our approximation, we assume the worst case -- that V_L = the peak voltage.

Therefore,

$$Vr \sim \frac{VpT}{R_L C}$$

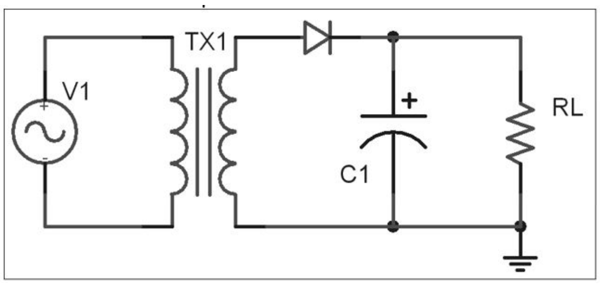
Now comes the true significance of what happens as a result of the quick charging through the diode: The DC voltage is much higher than it was for the unfiltered signal! We approximate the DC component of a filtered rectifier as follows:

$$Vave = Vp - \frac{Vr}{2}$$

Of course, this becomes a worst case approximation, because the ripple is a worst case approximation. In reality, the ripple will be less, and the average voltage will be higher than these calculations predict.

By the way, we will encounter circuits where the Load Current, I_L, is known, in which case we don't need to do the approximation and can just use the first formula to determine the ripple voltage.

Question: Use the schematic below to answer the questions that follow. V_1 is 120 VAC at 60 Hz, the transformer turns ratio is 10:1, the diode has a forward drop of 0.7 V, the capacitor is 220 μF, and the load resistance is 330 Ω.



1. What is the peak voltage across the load, referenced to ground? 16.3 V_p
2. What is the worst case analysis of the ripple voltage? 3.74 $V_{p\text{-}p}$
3. What is the worst case estimate of the average voltage? 14.4 V_{DC}

If you aren't satisfied with the "approximation" aspect of this, you could now use the average voltage instead of the peak voltage to do a new calculation, but you should discover that there is no appreciable difference in your new answer, because the ripple voltage is fairly small.

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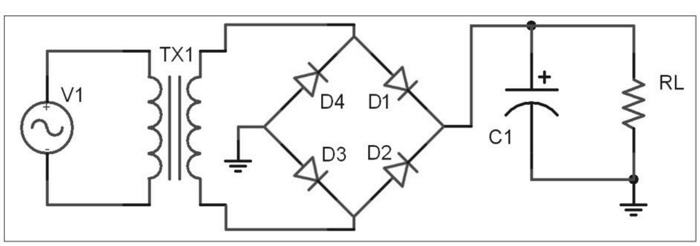


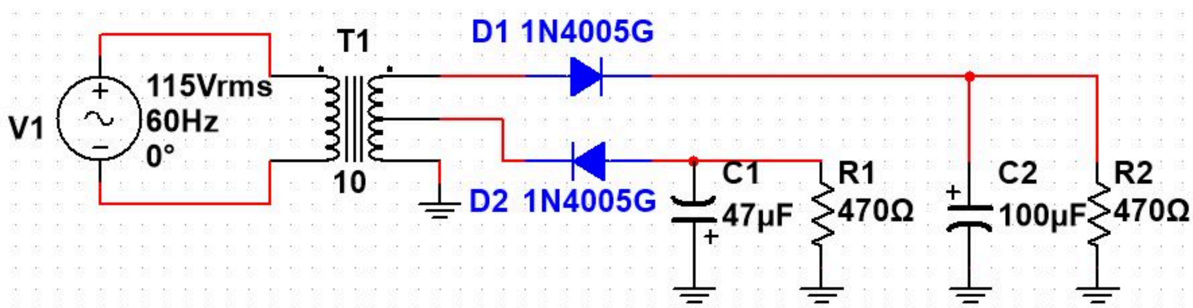
1. What is the peak voltage across the load, referenced to ground? 15.6 V_p

2. What is the worst case analysis of the ripple voltage? 1.79 $V_{p\text{-}p}$

3. What is the worst case estimate of the average voltage? 14.7 V_{DC}

From these two examples, it should be apparent that the full-wave rectifier circuit produces a much better filtered output than the half-wave, part of the reason this circuit is the most common one used in inexpensive linear power adapters.

Here's a worked example that will reinforce what you've already learned, while exposing you to some useful variations to the types of circuits you've been investigating.



At first glance, you may be tempted to say this is some kind of full-wave rectifier, since it has two diodes. However, upon closer inspection, it turns out it's two independent half-wave rectifiers: the diodes are connected to two separate load resistors (and their associated filter capacitors). In addition, the diodes are driven from different points on the secondary of the transformer, so the output voltages will be different in magnitude as well as polarity.

We'll analyze the two parts separately.

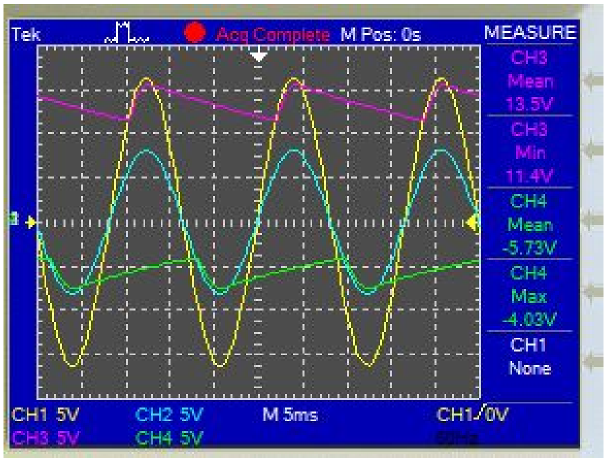
D1 Circuit

- Current flows through D1 during the positive half-cycle of the transformer signal, therefore this is a positive supply.
- The entire secondary signal appears across this circuit, so the peak voltage across the load would be $\frac{115 \cdot \sqrt{2}}{10} - 0.7 = +15.6\ V_p$
- Since only the positive half-cycle forward-biases D1, this is a half-wave rectifier with a frequency of 60 Hz and a period of 16.7 ms.
- The worst-case prediction for the ripple voltage would be $V_r = \frac{V_p \cdot T}{R_L \cdot C} = \frac{15.6 \cdot 0.01667}{470 \cdot 100\ x10^{-6}} = 5.52\ V_{p-p}$
- The worst-case prediction for the average voltage would be $V_{ave} = V_p - \frac{V_r}{2} = +15.6 - \frac{5.52}{2} = +12.8\ V_{DC}$
- The minimum voltage expected would be $V_{\text{min}} = V_p - V_r = +15.6 - 5.52 = +10.1\ V$

D2 Circuit

- Current flows through D2 during the negative half-cycle of the transformer signal, therefore this is a negative supply.
- The proper orientation for the electrolytic capacitor, C1, is positive to ground, negative to the more negative voltage as shown.
- Only half of the secondary signal appears across this circuit, so the peak voltage across the load would be $-\left(\frac{(115 \cdot \sqrt{2})}{10 \cdot 2} - 0.7\right) = -7.43\ V_p$
- Since only the negative half-cycle forward-biases D2, this is a half-wave rectifier with a requency of 60 Hz and a period of 16.7 ms.
- The worst-case prediction for the ripple voltage would be $V_r = \frac{7.43 \cdot 0.0167}{470 \cdot 47\ x10^{-6}} = 5.61\ V_{p-p}$
- The worst-case prediction for the average voltage would be $-\left(7.43 - \frac{5.61}{2}\right) = -4.63\ V_{DC}$
- The smallest negative voltage expected would be $-(7.43 - 5.61) = -1.82\ V$

The actual results for this circuit as simulated by Multisim are shown below, and, as expected, are better than the "worst case" predictions:



The ripple for the positive supply is only 4.2 $V_{p\text{-}p}$ instead of 5.52 $V_{p\text{-}p}$, the average is +13.5 V_{DC}, and the minimum voltage is +11.4 V.

The ripple for the negative supply is only 3.4 $V_{p\text{-}p}$ instead of 5.61 $V_{p\text{-}p}$, the average is -5.73 V_{DC}, and the minimum voltage is -4.03 V -- quite an improvement over the worst-case predictions. In fact, this part of the circuit would be suitable for a -3.3 VDC regulated supply, something our worst-case predictions would have ruled out due to the voltage dropping below -3.3 V.

In reality, it would be a good idea to increase the size of the filter capacitor for the second circuit. If we used a 100 μF capacitor instead of the 47 μF capacitor shown, the worst-case prediction for the minimum voltage would be -4.80 V, which is a huge improvement over the circuit as shown. We've already got a 100 μF capacitor in the parts list, so it makes good sense to use one here, too. (For practice, you might want to verify the minimum voltage value presented here.)