Power Supplies – Filter Capacitor

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The energy storage process of a capacitor is such as to oppose a change in voltage. The capacitor absorbs energy when the voltage tries to rise and releases energy when the voltage tries to fall. The raw rectified DC voltage has too much fluctuation to generally be useful for powering electronics. It should be intuitive that the physics of capacitor operation can be used to smooth the rectified voltage pulses.

The question becomes how much capacitance is required to achieve a given degree of smoothness in the DC voltage. It is very challenging to apply the mathematics for this to achieve precise answers since transcendental equations are involved which only have numerical rather than direct solutions. It turns out that precise answers are useless since capacitances are only available in coarse steps. All we need to do is to establish some reasonable approximation to guide our choice of capacitance. Although there is a definite inverse relation between capacitance and ripple voltage there is no definite answer as to what is right amount of ripple voltage. Thus, there is no singular correct value of capacitance for a given power supply application. The general concept is to use the smallest value of capacitance that results in an acceptable amount of ripple voltage. Before diving into the mathematics it is very instructive to just observe examples to gain an intuitive understanding.

The examples used in this article make use of a power transformer with an 8 volt secondary rated at 2.5 amperes. The typical voltage regulation for a 20 volt-ampere transformer such as this is 25 percent. The plotted simulations are from an Excel spreadsheet, rectifier_filter.xls, written by the author and available for download on the author's web site, http://www.kennethkuhn.com. Silicon diodes are used with a bulk resistance of 0.1 ohms. The AC line frequency is 60 Hz.

The first example is to illustrate half-wave rectification. Half wave rectification results in DC current in the secondary and thus makes poor utilization of the power transformer and is only used for low power applications where utilization is not an issue. Poor utilization means that most of the capability of the power transformer is not usable. In this example the design is such that the ripple voltage on the DC output is very obvious. It is also obvious that full-wave rectification would roughly halve the magnitude of the ripple voltage.

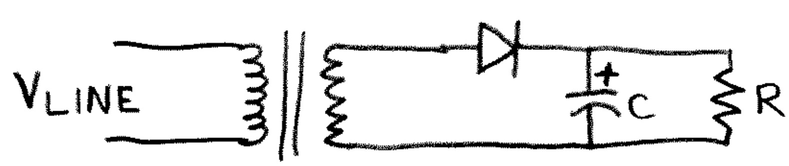

Figure 1: Half-wave rectifier circuit. C = 2,700 uF, R = 16 ohms

Power Supplies – Filter Capacitor

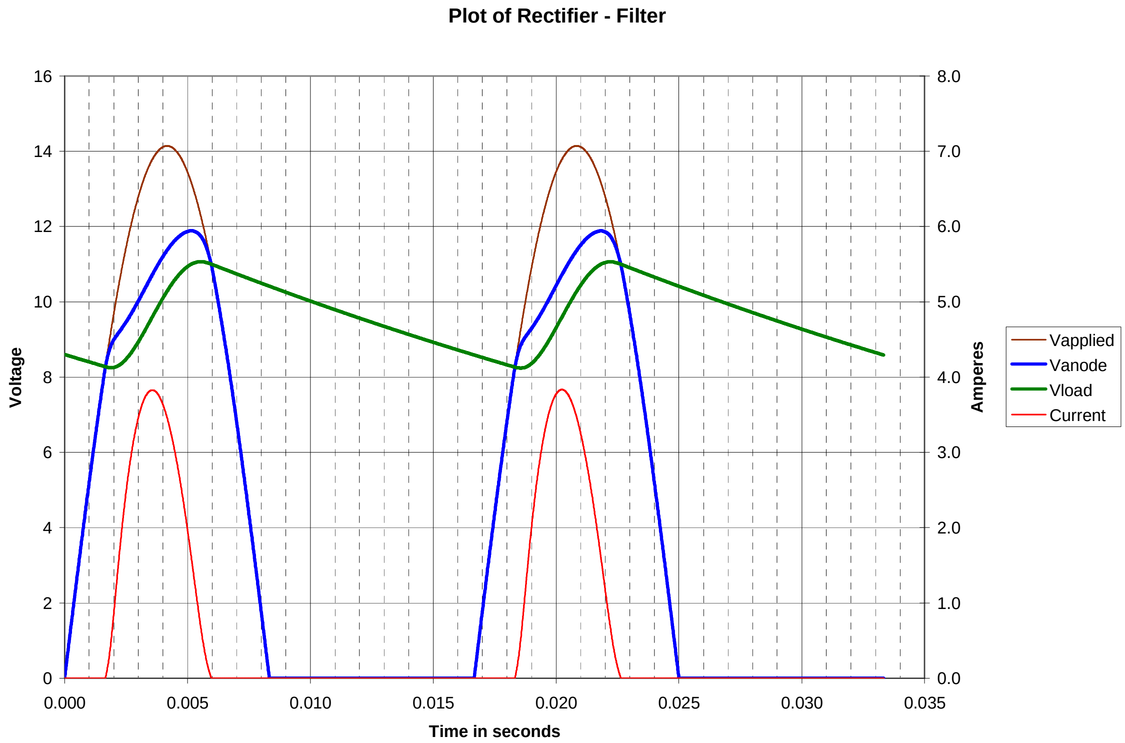

Figure 2: Half-wave rectifier. 9.6 VDC, 9% ripple

The large half sinusoid voltage peaks are the theoretical open-circuit output voltage of the transformer. The bold distorted half sinusoid voltage waveform is representative of the actual loaded voltage that could be measured at the secondary terminals using an oscilloscope. The distortion is caused by the fact that there is voltage drop across the transformer internal impedance during the time when current is being conducted. Observe that the lower partial half sinusoid waveform is the secondary current and conduction only takes place when the applied voltage waveform exceeds the voltage across the capacitor. Observe that the time constant when the capacitor is charging is relatively short because of the low impedance of transformer and diode. Observe that the time constant when the capacitor is discharging is much longer because of the higher resistance of the load. That must always be the case in any power supply and is the reason for the saw tooth appearance of the DC voltage waveform.

The most important voltage is not the DC average which is 9.6 volts but the DC minimum which is 8.2 volts. The load resistor is a simple substitution for a voltage regulator and its load. In reality the voltage regulator appears as a constant current load although the distinction is only subtle in most situations as the effective resistance is high in comparison to the source resistance of the rectifier and filter. All linear voltage regulators require a certain minimum input voltage higher than the regulated output voltage in order to stay in regulation. For a 5 volt regulator the typical minimum required input voltage is around 7.5 volts so this filter can work.

Power Supplies – Filter Capacitor

The maximum on the DC output waveform is 11 volts. Thus the ripple voltage is 2.8 volts peak-peak (11 – 8.2). Although the peak-peak voltage is important it is customary to measure ripple voltage in rms. The simulation calculates the rms ripple voltage to be 0.87 volts. It is common practice to specify the percent ripple relative to the DC average voltage and the equation is shown below.

%ripple = 100 * rms_ripple_voltage / average_DC_voltage   Eq. 1

The significance of the percent ripple is shown in Table 1.

% Ripple	Description
> 10	Very High
5 – 10	High
2 – 5	Medium
1 – 2	Low
< 1	Very Low

Table 1: Interpretation of Percent Ripple

Increasing the size of the filter capacitor lowers the ripple. Figure 3 shows the effect of increasing the filter capacitance from 2,700 microfarads to 10,000 microfarads.

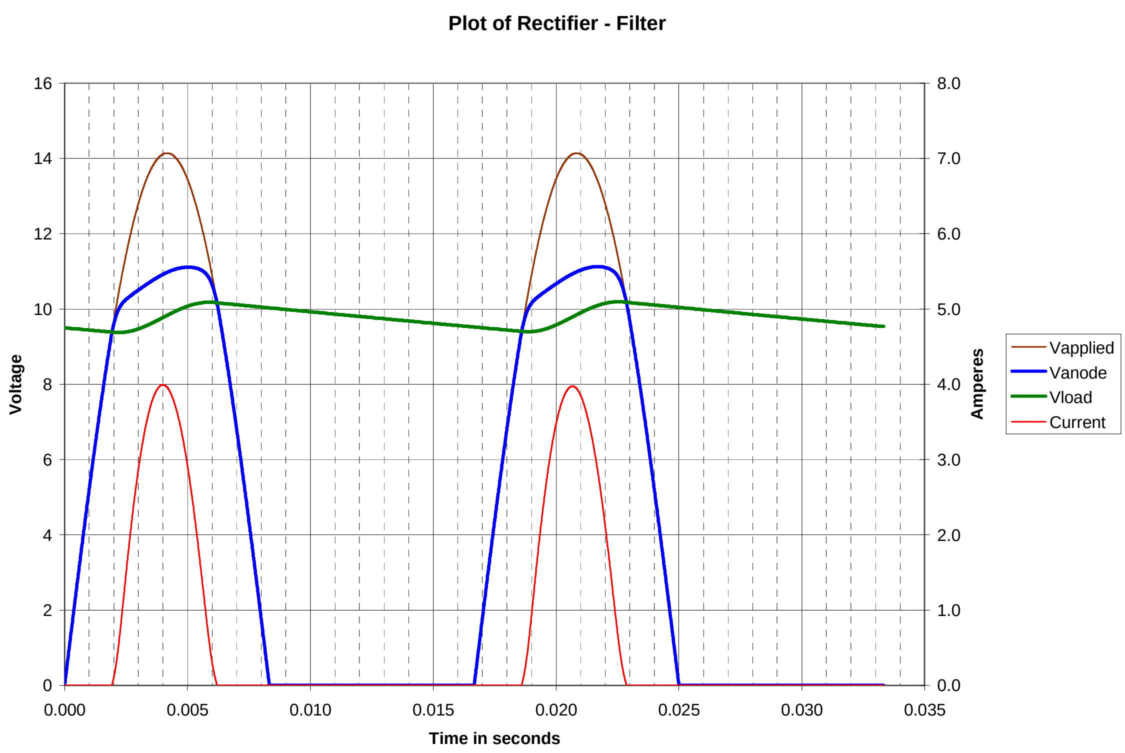

Figure 3: Increasing filter capacitance to lower ripple voltage

The average DC voltage increased to 9.8 volts and the DC voltage waveform varies from 9.4 to 10.2 volts resulting in 2.5% ripple which is in the medium range. Observe that the peak current through the diode increased to 4 amperes from 3.8 previously. Reducing ripple will increase the peak stress on the transformer and diode. There is always a trade-off between component stress and the amount of ripple.

Now it is time to explore full-wave rectification. The circuit is shown in Figure 4.

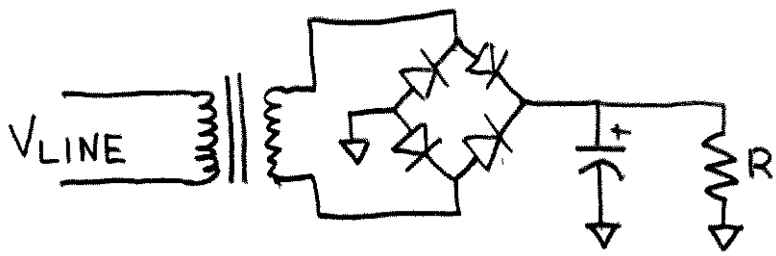

Figure 4: Full-wave Bridge Rectifier. C = 2,700 uF, R = 16 ohms

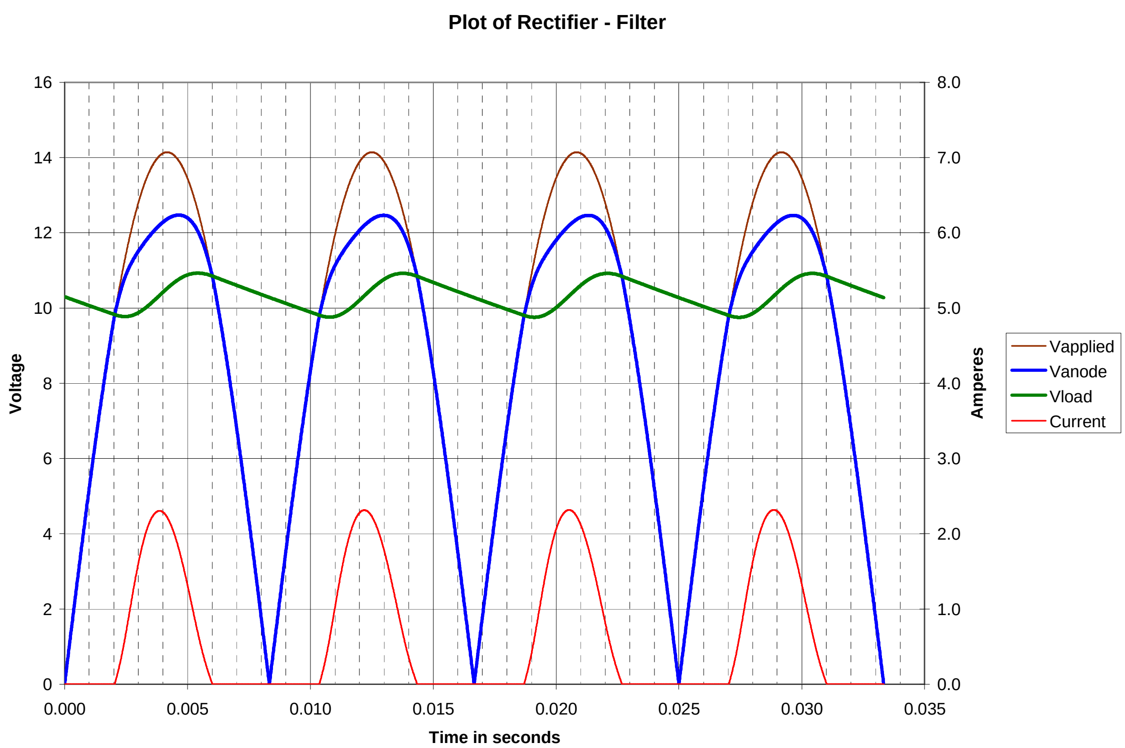

Figure 5: Full-wave Bridge Rectifier 3.7% ripple

The DC average voltage is 10.35 and the ripple is only 3.7% using the same size capacitor as in the first half-wave circuit. Observe that the current peaks are only 2.3 amperes. The ripple frequency is also twice the line frequency or 120 Hz.

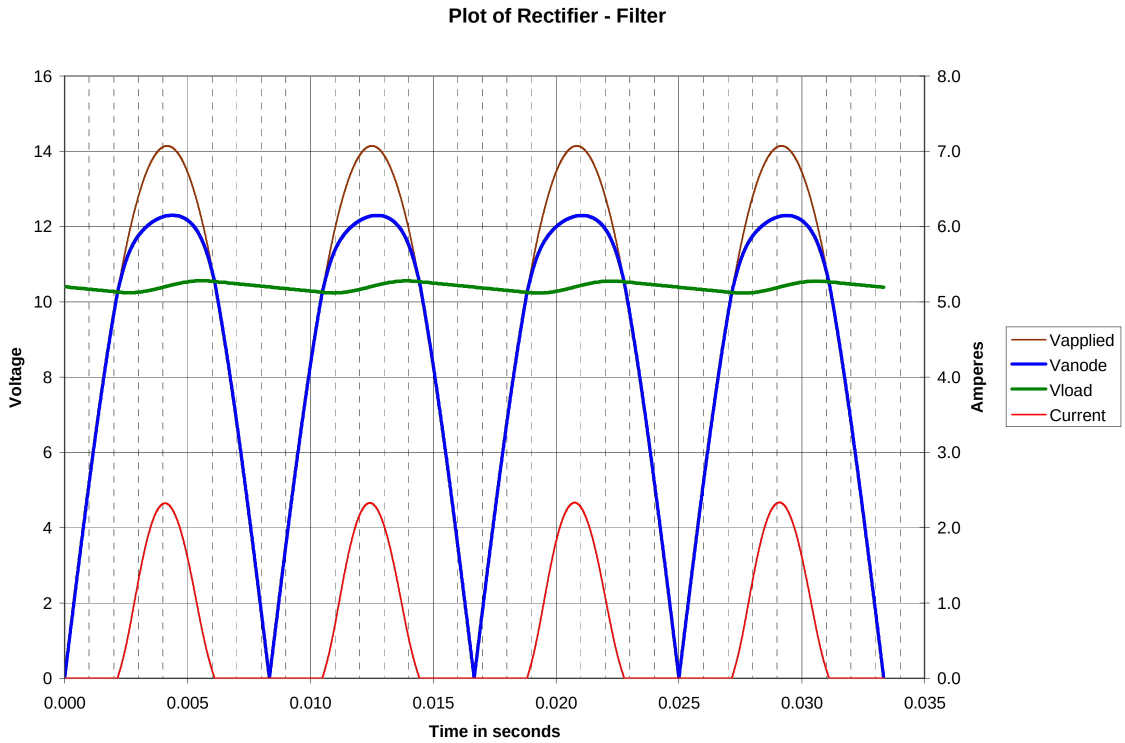

Figure 6: 10,000 uF, 1% ripple

Surge current at power on

So far we have been looking at the steady state condition. It is important to consider the stresses that occur at turn on. Figure 6 shows the turn on surge using the 2,700 uF capacitor to be about 6.7 amperes. Figure 7 shows the longer turn on surge using 10,000 uF to be a peak of 10 amperes. The turn on surge is highly stressful to the diodes and the capacitor. There are also associated high currents on the primary side of the transformer that can overstress the power switch if it is not rated for the peak surge. The average current rating alone is not enough. This is another reason why the general rule in capacitor selection is to use the minimum capacitance that results in acceptable ripple voltage.

Power Supplies – Filter Capacitor

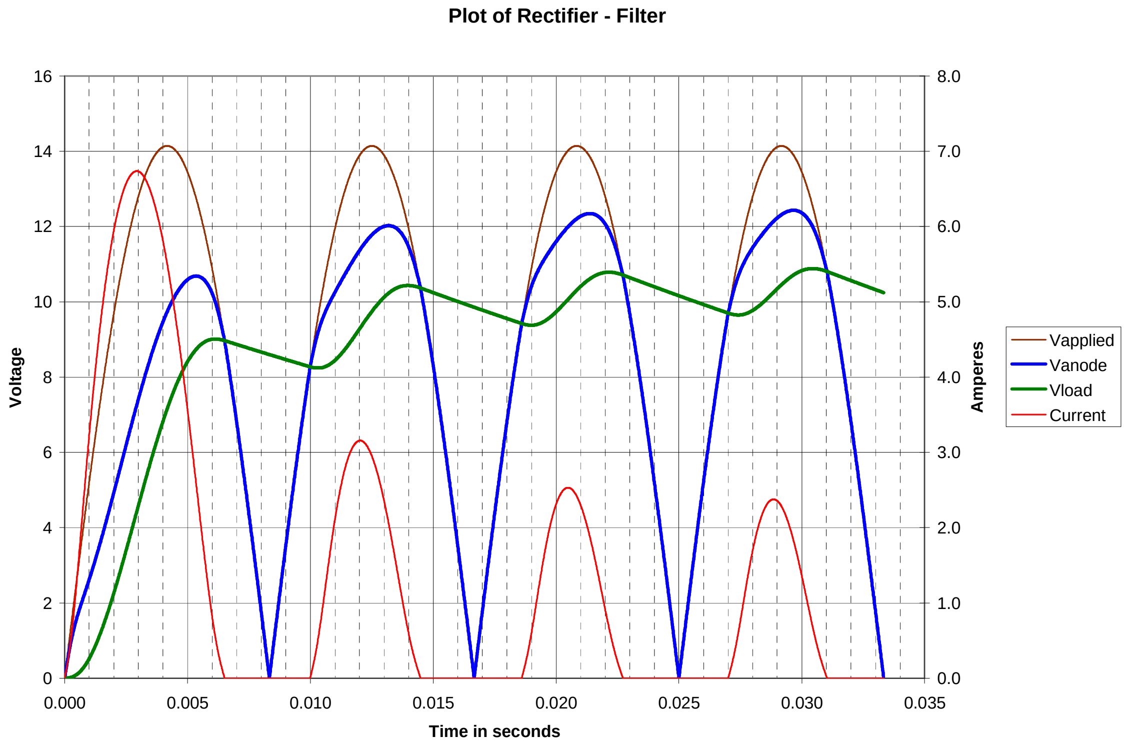

Figure 6: Start up 2,700 uF

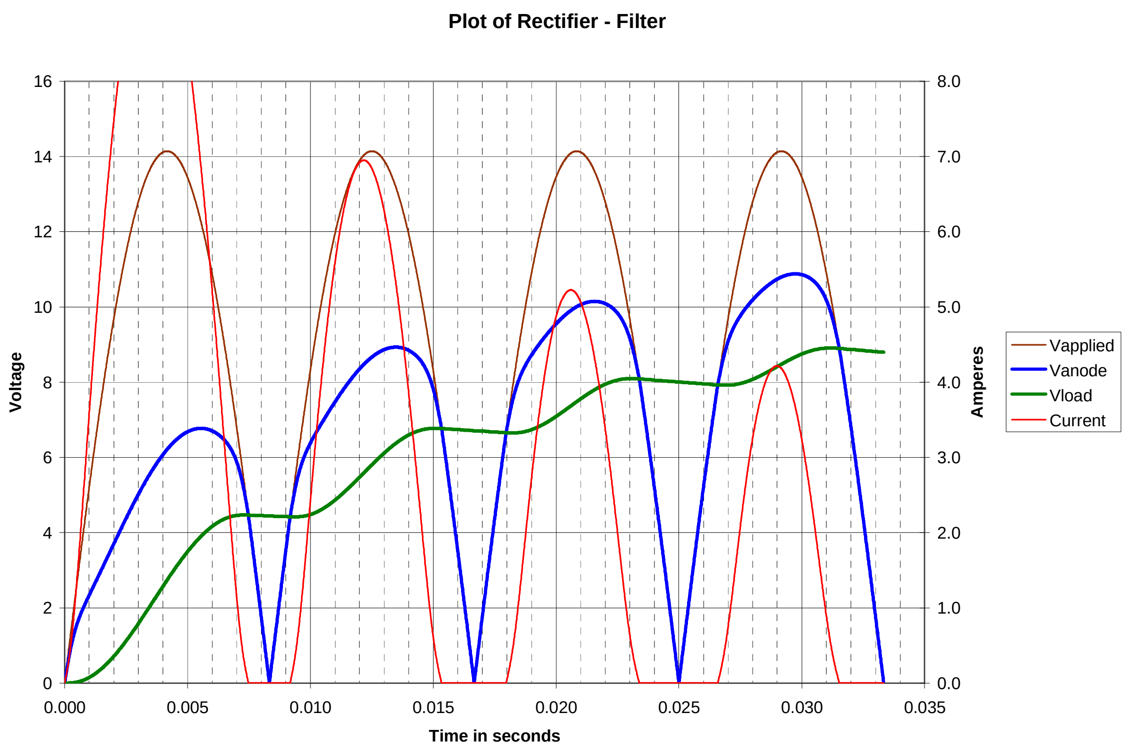

Figure 7: Start up 10,000 uF peak current is 10 amperes

Power Supplies – Filter Capacitor

Capacitor Sizing

The following equations provide the approximate capacitance required to achieve a given ripple percentage. These equations are generally good for ripple percentages less than 10 and are derived empirically. In general 3 percent ripple at the maximum load is reasonable. Calculate the required capacitance for nominal 3 percent ripple and then round up or down to the nearest standard size. Note that designing for 1 percent ripple takes three times the capacitance for only a marginal improvement – although there may be situations where that is important. Design always takes consideration of many variables and there is rarely such a thing as a singular solution.

$$C = \frac{24}{F * R * \%ripple}$$ for half-wave rectification Eq. 3

$$C = \frac{8.6}{F * R * \%ripple}$$ for full-wave rectification Eq. 4

where:

C is in Farads
F is the line frequency in Hz
R is the effective load resistance, Vo / Io

Stresses if "ideal" transformer is used

Suppose the transformer was nearly ideal with 0.1% voltage regulation and diodes with a bulk resistance of 0.001 ohms. The result is much higher peak currents as can be seen in Figures 8 and 9. These higher peak currents are more stressful to the diodes and the filter capacitor. It is initially counter-intuitive but an "ideal" transformer is not preferred for rectifier-capacitor applications. Leakage inductance in the transformer that is usually an imperfection is an advantage in power supplies because it causes the current pulses to be more spread out in time thus lowering the peak amplitude. Keep in mind that the same charge is transferred so the pulse areas are the same. If the width is reduced then the height must increase.

Observe in Figure 8 that the current pulses are 5.2 amperes and also that there is minimal voltage drop in the transformer thus loaded secondary waveform is not distorted. Note that the open circuit voltage of the transformer is essentially the same as the loaded voltage since the transformer impedance is so low. Figure 9 shows the huge turn on surge current and rapid charging of the capacitor. The peak of that surge is 37 amperes! Compare this plot to the more typical power on surge in Figure 7. There would be a very audible grunt when this system was turned on. Unless rated for high peak currents the power switch would suffer accumulative damage and fail prematurely.

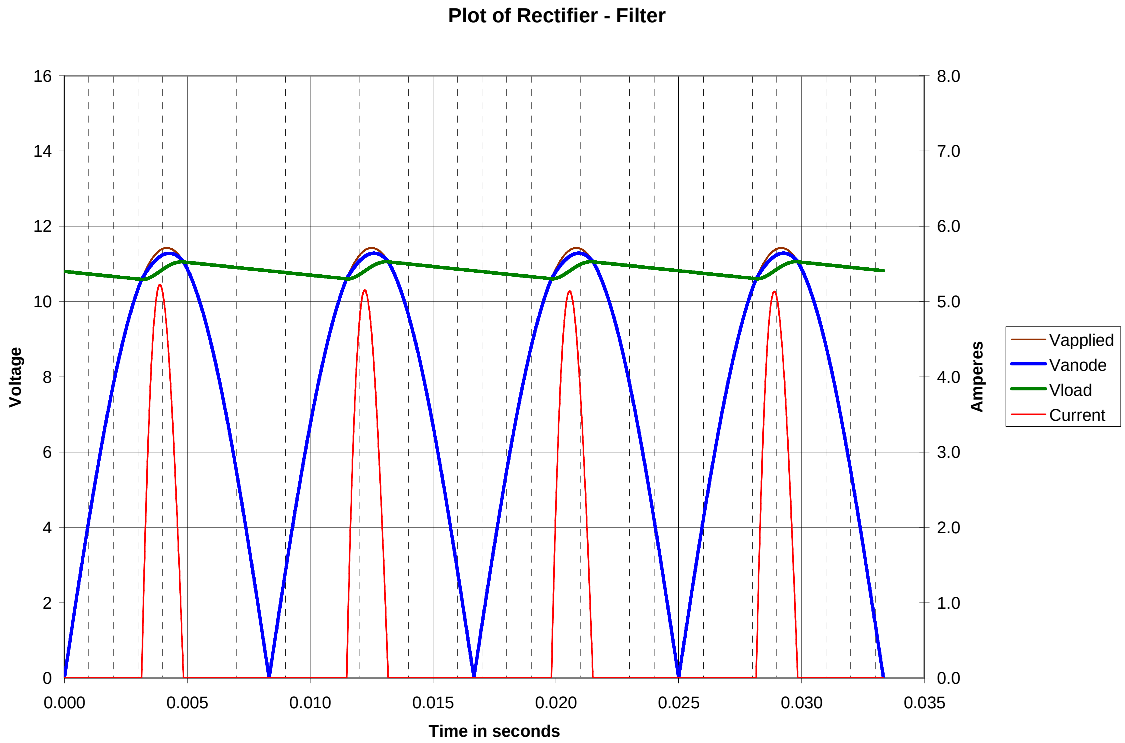

Figure 8: Near ideal transformer with low resistance diodes

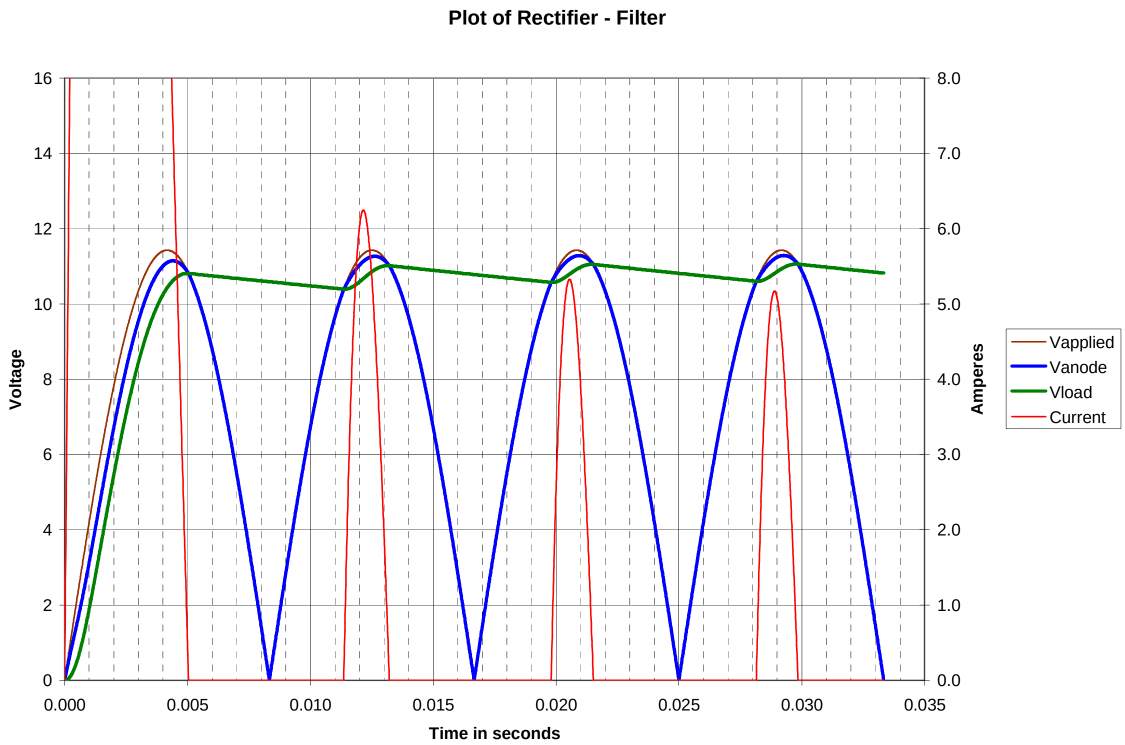

Figure 9: Turn on surge with near ideal transformer and diodes