

Description and Use of rectifier_filter.xls

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July 26, 2009

Introduction

The spreadsheet, rectifier_filter.xls, is designed to be a useful analysis and teaching tool for understanding the non-linear operation of a rectifier-filter set for converting AC line voltage to a smoothed DC voltage for use in various electronic systems. This spreadsheet permits a lot of experiments to be done with various configurations such as half-wave, full-wave center-tapped, and full-wave bridge.

For simplicity, this spreadsheet models the transformer as a sine-wave voltage source with linear output resistance. This gives good results for most cases but it should be noted that a real transformer is non-linear and also includes some inductance. In rectifier applications the inductance is a good thing as it causes the current pulses through the diodes to be more spread in time resulting in lower peak currents. At high output currents the effective source resistance of a real transformer increases as the core begins to saturate. That causes the turn on surge current to be somewhat more spread out in time and thus with a lower peak amplitude than this spreadsheet predicts.

User cells are in red with gray background. Other cells are locked to prevent accidental corruption. Enter the following parameters for the spreadsheet and then observe Chart 1 to see the time domain simulation. The following sections discuss in sequence the data to enter for a given simulation.

Transformer Data:

Enter the line frequency in Hertz. This would typically be 60 Hz for American systems but can be 50 Hz or any frequency of your choice.

Enter the rated secondary voltage If there are two windings for connection in series or parallel then use the series connection for full-wave center-tap and either the series or parallel connection for half-wave or full-wave bridge as appropriate.

Enter the rated secondary current If there are two windings for connection in series or parallel then use the series connection for full-wave center-tap and either the series or parallel connection for half-wave or full-wave bridge as appropriate. For reference the peak value of the rms current is shown in green to the right.

% Regulation This is a metric for how the transformer voltage drops with load current – the lower the number the better. Transformers with power ratings over a few hundred volt-amperes typically have about ten percent regulation. Low power transformers typically have around 30 percent regulation. Note that the spreadsheet limits your choice to be between 1 and 35 and the value actually

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being used is in green to the far right. Values less than 1 are not realistic and can cause numerical problems in the simulation.

Transformer calculations:

These are some basic calculations based on the user input data. The voltage-ampere (VA) rating of the secondary is calculated. The open circuit output voltage of the transformer is estimated based on the given regulation. This is taken to be a sine wave although significant flattening of the peaks would be observed if measured with an oscilloscope. Based on the given regulation the effective source resistance of the transformer is calculated. Based on the given regulation the power dissipated by the secondary system of transformer is calculated if the transformer is fully loaded into a resistance. The resistance required to fully load the transformer is calculated.

Simulation Parameters:

Enter the starting phase for simulation. The starting phase of the AC sine wave can be any desired value. The least stressful starting occurs with low starting angles such as 0 degrees. The most stressful (highest peak charging current) occurs with starting angles in the vicinity of 90 degrees. In reality the starting phase is random so this simulation enables one to evaluate the possibilities.

Enter the number of cycles per plot. This value is limited to be between 1 and 25 and the value being used is shown in green to the right. A value of 2 provides good steady-state illustrations. Larger values may be useful in showing the turn-on transient. This value, N, also affects the number of sample points per cycle which is $4800 / N$ and is shown in green to the far right.

Rectifier Parameters:

Enter the mode. The choices are (1) for half-wave rectification, (2) for full-wave center-tap rectification, and (3) for full-wave bridge rectification. The spreadsheet constrains the choices to the above and the actual value being used is in green to the far right.

Enter the maximum diode junction voltage. This is normally 0.75 volts for silicon diodes and about 0.45 volts for Schottky rectifiers. The spreadsheet uses this value in constructing the model for the diode. This voltage should be interpreted as the maximum junction voltage that will occur for the peak currents expected in the simulation. This voltage does not include the effect of bulk series resistance in the diode that can cause the terminal voltage to be significantly higher – over 1 volt. The spreadsheet correctly adjusts for multiple diodes in series as occurs in the full-wave bridge configuration so enter the value for a single diode.

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Enter the bulk resistance of the diode. This is the bulk resistance of a single diode. The spreadsheet correctly adjusts for multiple diodes in series as occurs in the full-wave-bridge configuration. The bulk resistance goes down with increased current rating and can be obtained from data sheets or by measuring the slope of the current-voltage transfer curve at high currents where it is a straight line. The table with yellow background to the right provides some suggested values if hard data is not handy.

Filter and load Parameters:

Enter the filter capacitor in Farads. Be aware that there is a minimum allowable capacitance based on the sampling time of the simulation. If the capacitance you enter is too small a red notice will be printed and your value will be replaced by the minimum value. The minimum that can be used is shown in the Preliminary Calculations section. An estimated value that is for reference only to provide about 3% rms ripple is shown in green just above this cell.

The spreadsheet estimates the full load voltage, current, power, and effective resistance assuming 3% ripple. These values are provided for reference only and may be an aid in choosing an operating condition. Ignore these if you like.

Enter the load resistance. Enter either the estimate from above or a particular value of interest.

Preliminary Calculations:

These are calculations for the purpose of entering into the model. The total series charging resistance is found by adding the transformer source resistance to that of the series diode(s). The sampling time is found by dividing the time period of one cycle by the number of points per cycle from above. The minimum capacitance for the simulation to be numerically stable is calculated and if more than the user entered is then substituted for the user value and red note is printed by the user value. The charging and discharging time constants are computed – the discharge time constant should be significantly longer than the charging time constant. The next three lines are for the effective diode model and are the total junction voltage, total bulk resistance, and a factor for the hyperbolic tangent model. The open circuit peak of the sine wave is computed and the frequency is converted to radians per second. The final value is a constant for numerical integration and is the sampling time divided by the capacitance.

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Summary Results:

The summary results are grouped by color to make it easier to find things as there is a lot of data presented.

Enter the starting voltage This is the only user input cell for this section and is located just above the load voltage column (i.e. voltage across the capacitor). Use a starting voltage of zero to observe the turn-on transient. Then enter the Ending voltage (which is the last data point in the plot) value in the cell above several times as required until Ending equals Starting. At that point in time the turn-on transient has fully settled and the Summary Results calculations are correct. The peak diode current is always correct for whatever is shown on the plot but the other values are derived from calculations based on the plotted data.

VDC average This is the average of all of the DC data points in the simulation.

VDC max. This is the maximum value of DC voltage in the simulation.

VDC min This is the minimum value of DC voltage in the simulation.

VD max This is the peak voltage across the diode(s) junction. It will be a single diode drop for half wave and full-wave center-tapped and will be two junctions in series for full-wave bridge.

Vpp ripple This is the difference between VDC max and VDC min.

Vrms ripple This is the true rms calculation of the ripple on the DC voltage. It is the square root of the average of the squares of all of the DC voltage points minus the DC average.

% ripple This is 100 times the rms ripple voltage divided by the DC average voltage. The ripple factor is this value expressed as a decimal rather than as a percent. The following chart is a rough guideline for interpretation.

<u>% ripple</u>	<u>Comments</u>
>10	Very high
5 to 10	High
2 to 5	Normal or Typical
1 to 2	Low
< 1	Very low

ripple PP/rms This is the ratio of the peak-peak divided by the rms ripple voltages and is provided for reference. A common approximation to obtain true rms is to divide the much easier to measure peak-peak by three assuming that the ripple is not very high. This metric provides the exact value for comparison.

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Amperes DC load current This is the actual DC load current.

Amperes capacitor ripple current This is the ripple current through the capacitor and is obtained by dividing the rms ripple voltage by the reactance of the capacitor at the ripple frequency (line frequency for half-wave, twice line frequency for full-wave). This is a very important metric because all capacitors have a maximum allowed ripple current. You must choose a capacitor for a design that has a higher ripple current rating.

Amperes peak diode This is the peak current through each diode. The diode must be rated to a higher peak current level than this value. This value is also correct when starting from zero to instrument the peak starting surge.

Amperes avg. diode This is the average current through each diode in the rectification system.

Peak/avg current This is the ratio of the peak to average current in each diode. It is provided here as a point of reference.

Irms, transformer secondary This is the rms current in the transformer secondary

Transformer Peak / Rated This is a metric of the peak actual secondary current to the peak rated current assuming full sinusoidal load current. In general the value should not go too far beyond 1.0 although how far depends on a number of variables in the transformer design.

Watts load (DC + ripple) This is the power delivered to the load.

Watts diode dissipation total This is the total dissipation of all diodes in the rectification system.

Watts each diode This is the dissipation of each diode in the rectification system. It is half the total for full-wave center-tap since each diode is used only half the time. It is one-fourth the total for full-wave bridge.

Watts secondary dissipation This is the dissipation in the source resistance of the transformer.

Watts total This is the total power delivered to the load and dissipated as losses.

Watts, DC average This is the average DC output voltage multiplied by the average DC output current.

% efficiency, secondary This is that of the secondary circuit only. The real efficiency of the complete system will be lower, perhaps significantly lower, because of primary and core losses in the transformer. This value is provided as a

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general gauge. The detriments to efficiency are transformer voltage drop with load and diode losses. A better quality transformer and lower-loss diodes will improve efficiency.

% Transformer loading This is a metric that is the actual secondary dissipation divided by the secondary dissipation if the transformer were driving a purely resistive load at its full ratings. When equal to 100% the transformer secondary heating is the same as for a full resistive load even though the DC output power may be quite a bit less than the volt-ampere rating of the transformer

Transformer Utilization Factor This is the actual DC output power delivered to the load divided by the volt-ampere rating of the transformer. It will be observed that half-wave produces the lowest utilization and the full-wave bridge produces the highest utilization with the full-wave center-tap somewhat less than the full-wave bridge.

Diode model

It is always a challenge to simulate the operation of diodes with any degree of realism because there is no closed-form math that can calculate an operating point – numerical iteration is the only method that works. Numerical iteration for a spreadsheet with thousands of points is unwieldy. Thus, a simpler method is needed that provides practically the same result. After some study and experimentation the following approach was developed.

For the case where the applied voltage is less than that across the capacitor the current is obviously zero (ignoring tiny leakage currents that are not part of this simulation).

For the case where the applied voltage is greater than that across the capacitor the following equation is used for the current.

$$I = \frac{V_A - V_C - V_D}{R_A + R_D} \quad \text{Eq. 1}$$

V_A is the applied instantaneous sine wave voltage

V_C is the present voltage across the capacitor

V_D is the voltage drop across the diode(s) (junction only, excluding bulk resistance)

R_A is the source resistance

R_D is the bulk resistance of the diode(s)

This equation looks simple enough except that V_D is an exponential function of I and there is no closed-form math to make Equation 1 solvable.

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However, it is known that V_D will generally be in the 0.6 volt region when the diode is conducting with little regard to the current. The significance of this is that the exact value of V_D means little when V_A is much larger than V_C . The only time when V_D is important to the simulation is when V_A is only a fraction of a volt larger than V_C . The important conclusion of this is that V_D can be estimated based on the difference between V_A and V_C .

$$V_{D_{\text{estimate}}} = K1 * \tanh(K2 * (V_A - V_C)) \quad \text{Eq. 2}$$

$K1 = 0.75$ for a single silicon diode and 1.5 for two in series (full-wave bridge)

$K2 = 0.7/0.75$ for a single silicon diode and $0.5*0.7/0.75$ for two in series

The 0.75 would be replaced by roughly 0.45 for Schottky diodes.

The above constants were derived by empirical methods considering diodes in general and there is room for adjustment to model a particular diode more accurately but the general approach used in the spreadsheet gives good enough results for most applications. The beauty of this model is that it does a good job of modeling diode behavior at low voltage drops and it naturally limits the junction voltage to the maximum provided (i.e. 0.75) when the current would be significant. The ultimate beauty is that no iteration is required. This is an example of using an approximation that although is only applicable to specific problems produces excellent results even though the math is only a distant relation to the actual math being modeled. Clever engineers often employ such methods to simplify difficult problems. Purists who worry too much about exactness never discover these methods. Results are what matters. Life does not have to be perfect.