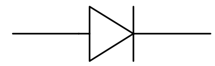
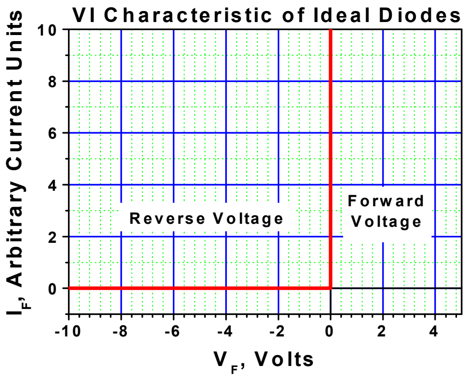
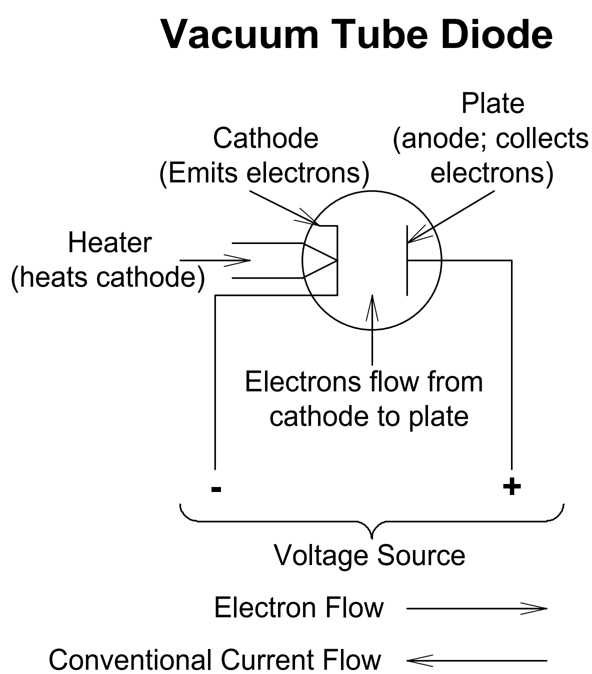
DIODES AND POWER SUPPLY DESIGN

Diodes and Ideal Diode Behavior

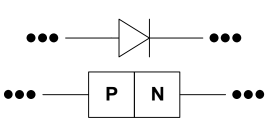
The basic character of diodes is that current can flow easily in one direction[1] and cannot flow in the other. For ***ideal diodes***, this is the behavior of a device that is a ***short circuit*** for current flow in the ***forward direction*** and is an ***open circuit*** for current flow in the ***reverse direction***. The circuit symbol for a diode is  and the triangle indicates the direction current can flow easily. Shown in the figure is a ***voltage-current*** (or **VI**) graph of ***ideal diode*** behavior. Although it will be necessary to adjust the ***VI*** graph later when we consider the consequences of real diode behavior, the ideal description is sufficient for introducing diode applications.



Before discussing applications, we will briefly consider how this type of electrical behavior can be accomplished. Vacuum tubes, the diode version of which is shown schematically in the figure, provide one easy-to-visualize way. Since the only source for electrons is the cathode (coated with a material which releases electrons on heating), electron flow can be in only one direction. (Note that electron flow, the flow of negative charge, is opposite to that of conventional current. Conventional current is the direction of positive charge.) Thus there can be no flow from plate to cathode.



Our primary interest will be ***semiconductor junction diodes*** in which the one-way behavior is the result of the junction between ***P-*** and ***N-type*** semiconductors. P- and N-type semiconductors are the result of intentionally introducing a controlled amount of impurity in an otherwise highly pure material, usually silicon. (This is referred to as ***doping***.) To create P-type material, the impurity is from an element one column to the left of silicon in the periodic chart; thus the impurity atom has one less electron than silicon and is thereby ***positive*** relative to silicon. Similarly, N-type materials are created by doping the silicon with atoms in the periodic chart column one position to the right, thereby creating a ***negative*** region. This arrangement can be sketched as shown in relation to the schematic symbol for diodes.



Schematic View of Junction Diodes

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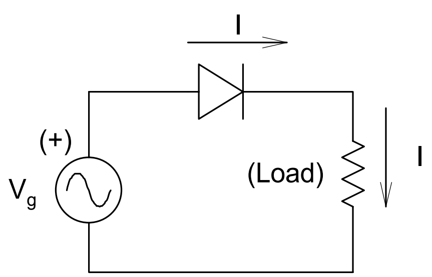
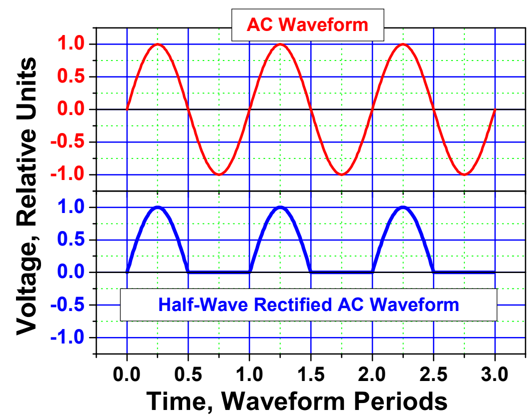
[1] Some of you may be familiar with ***check valves*** which exhibit the fluid-flow equivalent of diode behavior.

Applications of Diodes— Converting AC to DC

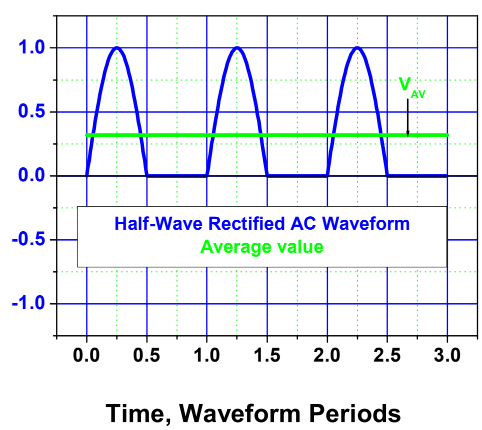
Electronic circuits need a source of ***steady*** DC as their power supplies. However, the standard house supply is AC (nominally 120 V_{rms} @ 60 Hz). To use the house supply to power electronic devices, it is obviously necessary to convert the AC to DC. Because of their one-way characteristic for current flow, diodes can do this. For example, consider the circuit below: When the upper side of the generator is positive as shown, current will flow in the direction indicated; when the lower side of the generator is positive, no current can flow. The result is a voltage across the ***load*** (represented by the resistor) in relation to that of the generator as shown in the graph.





Filtering

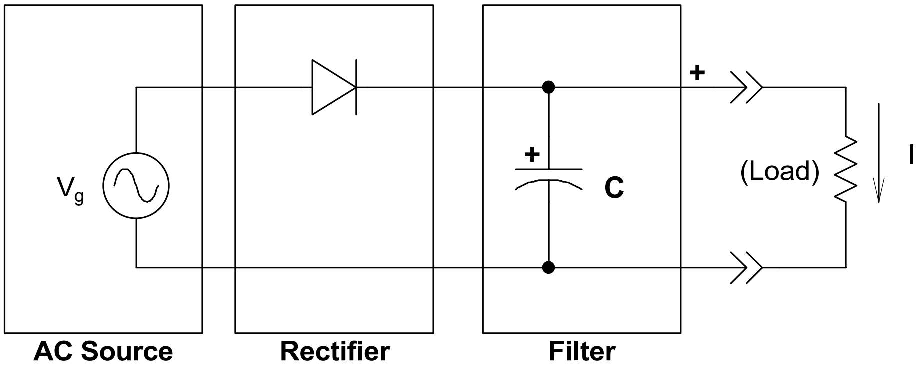
While the current through the load flows in only one direction and thus is DC in the strictest sense of the term, it isn't very steady. To ***smoothe out*** the voltage (current) requires ***filtering***. One way to view the filtering problem is consider the half-wave rectified waveform: it has a non-zero average value to which is added the non-steady component as indicated below: The average value can be considered the DC component and the non-steady part the AC component. Thus, the total voltage can be viewed as $V = V_{DC} + V_{AC}$. From this perspective, the filtering problem is that of ***passing*** the DC part (f = 0) and ***rejecting*** the AC part (f > 0). This describes the ***low-pass*** filtering task as discussed in connection with AC.



The standard low-pass filter discussed previously of course is suitable. However, it is more common to accomplish the desired filtering with only the capacitor and no resistor. While this accomplishes the function of low-pass filtering, its behavior is more directly described by recalling that capacitors ***store*** charge; thus the capacitor behaves to the load as a water storage tank does to the customers it serves.

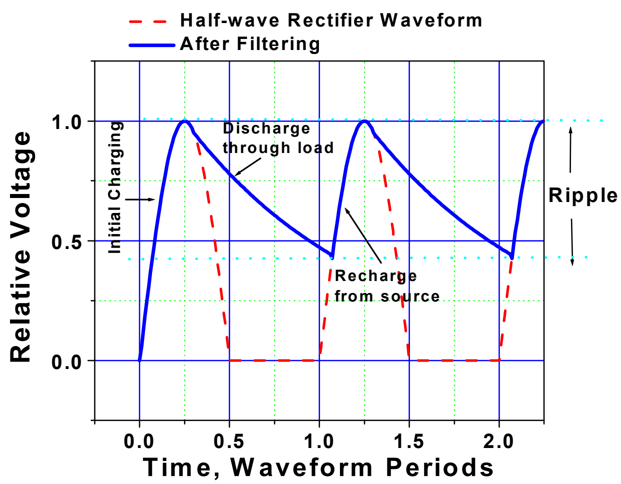
Behavior of Filter Capacitors

At this point, we can view a power supply as a collection of subunits as shown below:



Power Supply, Block Diagram

Behavior of this circuit can be summarized as follows: The source provides charge to the filter capacitor (and load) as long as the upper terminal of the generator is at a voltage equal to the voltage across the capacitor. (Remember that the diode has "ideal" character.) When the generator voltage reaches its peak value and begins to drop, the voltage across the capacitor is greater than V_g. During this time, the capacitor, in its "storage-tank" role, provides a flow of charge to the load. However, as charge is drained from the capacitor V_C drops proportionally. Nevertheless, for a ***suitably chosen*** capacitance, the drop in V_C (which equals V_{out}) is less than that of the unfiltered half-wave waveform. As soon as the generator voltage rises to a value equal to that reached by the capacitor, a new supply of charge is delivered to the capacitor and the cycle begins again. This behavior is illustrated in the graph.



An obvious question to consider at the beginning is that of a ***"suitably chosen"*** capacitor. One way to get a suitable starting value for a filter capacitor is based on the following relation:

$$\text{ripple} = \Delta V_C = \frac{\Delta Q}{C} = \frac{I_L \Delta t}{C} = \left(\frac{V_L}{R_L}\right)\left(\frac{\Delta t}{C}\right)$$

Built into this relation is the approximation that the current (charge flow) from the capacitor is constant throughout the discharge time Δt; as mentioned above, discharge actually follows an exponential decay. Moreover, approximation of the discharge by a linear function overestimates the amount and makes this a conservative estimate. Also, this relation requires a value for the discharge time Δt. An exact value for Δt requires calculation of the intersection between the

$$C = \left(\frac{V_L}{R_L}\right)\left(\frac{\Delta t}{\text{ripple}}\right) = \left(\frac{V_L}{R_L}\right)\left(\frac{T}{\text{ripple}}\right) = \left(\frac{V_L}{R_L}\right)\left(\frac{1/f_{supply}}{\text{ripple}}\right)$$

exponential discharge and the sinusoidal recharge curves. Setting Δt equal to the period ($T = 1/f$) of the waveform is another conservative overestimate. Fortunately, a conservatively approximate approach is suitable since real capacitors are not available in "exact" values, anyway. Thus, we can solve the relation above for C to find the parameters important is selecting the ***"suitably chosen"*** value.

Example:

Design targets:

1. $V_L = 9V$ @ $I_L = 150$ ma;
2. ripple $\leq 0.2V$;

Given: $f_{SUPPLY} = 60$ Hz

$$C \approx (0.15A)\left(\frac{1 \text{ sec.}}{60 \times 0.2V}\right)$$

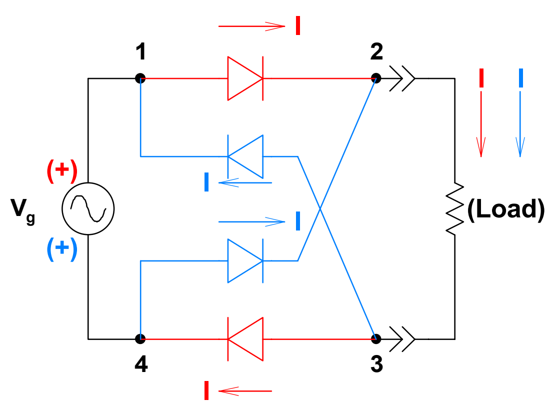
$$= 1.25 \times 10^{-2}F = 1.25 \times 10^{4}\ \mu F$$

This is actually a **large** capacitance value for a fairly modest set of design targets. In fact, a typical $1.0 \times 10^{4}\ \mu F$ (16 working Volts DC) capacitor has dimensions 18mm diameter x 36.5mm long, and costs $3.67.

Obviously, V_L, I_L, and ripple are design targets specified by the "customer" (*i.e.,* the load). We see clearly that ***less*** ripple is the result of ***more*** capacitance. Also, for the ***same*** capacitance, less ripple would occur for **less Δt.** This is a point worth pursuing since our rectifier only "uses" half the voltage waveform. In other words: can we find a way to make use of the total waveform from the generator?

Full-Wave Rectifier Circuits

Using the full waveform amounts to "filling in" the gap of the half-wave circuit's waveform. Consider the circuit to the right: When the upper terminal of the generator is positive, current flow follows the "red" path; when the lower terminal is positive, current flow follows the "blue" path. In both cases current flows through the load in the ***same direction***. The result is that current is provided to the load during both half-cycles of the AC source.

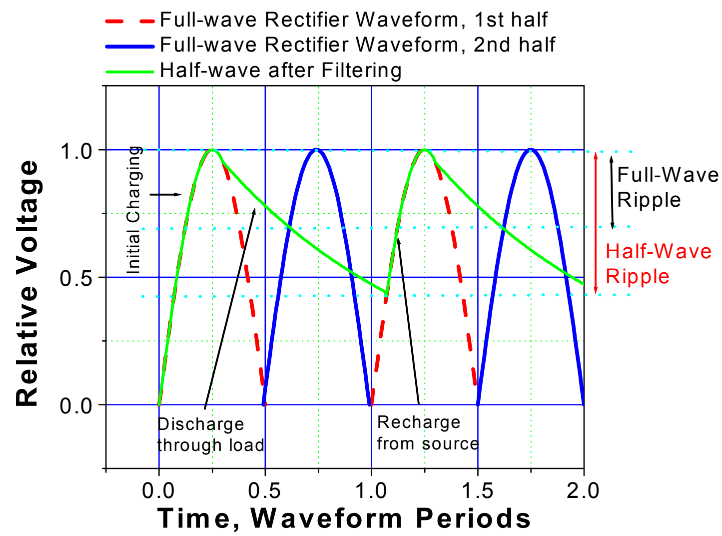


Full-Wave Bridge Rectifier

FAQ's: Why doesn't the current follow the "allowed path **3 -> 4 -> 2 -> load -> 3** (or, **3 -> 1 -> 2 -> load -> 3**)? The answer is that there is no voltage source in either of the loops, and, without a voltage source, no current will flow. The voltage source is the generator and is only in the loops **1 -> 2 -> load -> 3 -> 4 -> V_g -> 1** (for the "red" path) and **4 -> 2 -> load -> 3 -> 1 -> V_g -> 4** (for the "blue" path).

The result of this ***full-wave*** rectification scheme (referred to as the "full-wave bridge" rectifier circuit) is shown in the graph. From the graph, it is also clear that the full-wave ripple ***for the same capacitance*** is roughly one-half that of the half-wave amount.

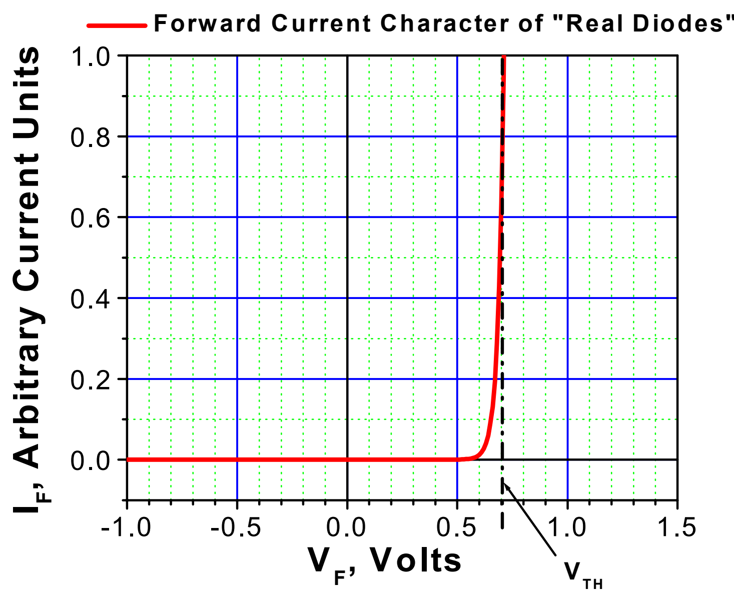
The cost for using a full-wave bridge (***FWB***) rectifier versus a half-wave circuit is that of 3 diodes. However, diodes are cheap–those used in our lab cost less than $0.05 each! On the other hand, the benefit, in terms of reduced ripple is high, particularly if we recall that it would take an additional $3.00-capacitor to equivalently reduce the ripple otherwise.



Conclusion: Our ***normal*** rectifier circuit from now on will be the ***FWB*** configuration. However, we still cannot produce ***perfectly*** smooth DC with our power supply. The final section we need to add to the power supply design is a ***voltage regulator***. Before we can do so, we need to return to our description of diode behavior and make it more realistic. In doing so, we will also introduce a non-ideal characteristic of real diode behavior useful for voltage regulator applications.

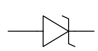
Reality Check for Diode Behavior

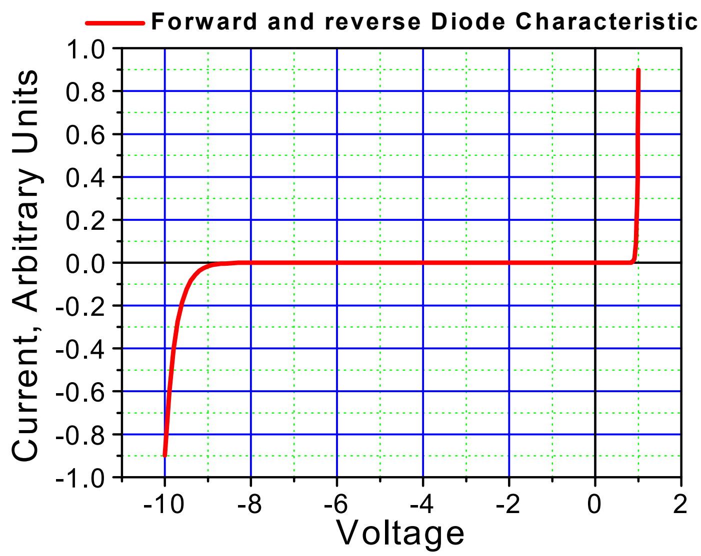
To this point, we have considered diodes to have the ***ideal behavior*** described above. It is time now to add realism to our description of diode behavior. From the more realistic description shown in the figure, we can see the main adjustment we need to make: the forward conduction requires a non-zero forward voltage. In other words, there is a forward threshold voltage (***V_{TH}***) which must be established before any current flows. (In the graph shown, ***V_{TH} ~ 0.7V***.) This means a diode behaves to current flow like a dam behaves to water flow: Unless the water level (voltage) reaches the top of the dam (the threshold), no water (current) flows. The forward threshold voltage is a characteristic of the semiconductor material (*e.g.,* silicon *vs.* germanium) and the construction of the diodes (*e.g.,* shottky *vs.* standard). However, the value is always in the range 0.4V to about 1V. Some examples are shown in the table below.



Material / construction	**V_{TH}**
Silicon / Standard	0.7 V
Silicon / Shottky	0.4 V
Germanium / Standard	0.4 V

Also seen in the forward-current graph is curvature of the VI characteristic as conduction begins, and a large, though finite, slope for conduction. We can ignore these behaviors for our remaining purposes; thus, our ***improved*** description of the forward-behavior of diodes is that conduction begins abruptly (with infinite slope) when the forward voltage reaches the threshold value (***V_{TH}***).

Important tor the ***voltage regulator*** objective for our power supply design project is the behavior of diodes in the reverse direction. Actually, they don't act like perfect open circuits! In fact, there is a reverse-voltage value at which the diode will "break down" and begin conduction, a condition usually destructive. In recognition of this, diodes are usually characterized by their ***current capability*** and the ***peak inverse voltage***. (In the lab, we typically use type 1N4007 diodes having ratings 1A and 1000 PIV.) It turns out however that the reverse conduction characteristic can be engineered to values in the range ~4V to ~100V, and that it can be made non-destructive. Diodes designed and constructed for this purpose are called ***Zener diodes***, given the symbol  , and the effect is the ***Zener effect***. The graph to the side shows both the forward and reverse characteristics of a "real" diode.



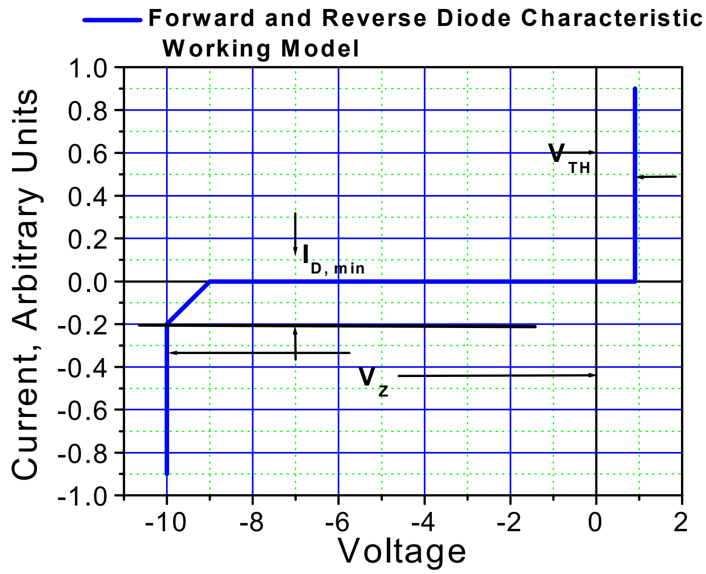
Obvious from the graph are the following characteristics of conduction in the reverse direction:

1. There is a "threshold" reverse voltage (***Zener Voltage)*** for the onset of reverse conduction;
2. Reverse conduction ***does not*** begin abruptly, but ***does*** reach a large slope (approaching infinite);
3. The slope reaches the "large" value when the reverse current reaches and exceeds a "threshold" value (*e.g.,* approximately 0.6 in the graph shown).

Our interest in the Zener effect comes from the adjustable value of the Zener voltage and the near-infinite slope of the reverse VI characteristic. It is possible to use these behaviors in one approach to voltage regulation.

"Improved" Model for Diode VI Behavior

Based on our needs for this course, we can now establish our working model for (description of) diode behavior as that shown in the graph. Key elements of the characteristic are: ***(1)*** the threshold voltage for forward conduction V_{TH}***; (2)*** The ***Zener*** Voltage in the reverse direction , V_{TH}; ***(3)*** the ***minimum*** diode current for reverse conduction to before onset of the near-infinite VI characteristic of the Zener effect.

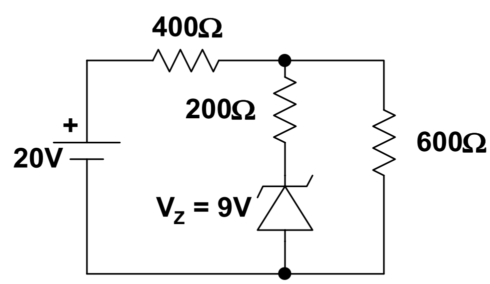


Important about the infinite slope of the VI characteristic is that the ***voltage*** across the diode is constant ***regardless of the current through it***. This is the property (along with the adjustability of V_Z) making the Zener effect useful for voltage regulator applications.

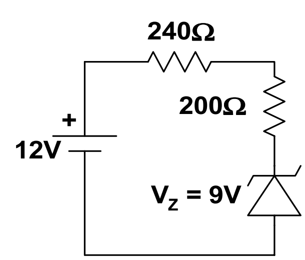
Examples of Diodes in DC Circuits:

1. Calculate the current through the diode and all resistors in the circuit shown. (For this example, ignore $I_{D,min}$. That is, assume current to flow abruptly as $V = -V_Z$.)

Solution: The central question is whether or not the Zener threshold voltage of the diode will be reached. If so, current will flow in the center branch; if not no current will flow in that branch. This is most easily tested by application of Thevenin's theorem.



At the open terminals created by "disconnecting" the branch containing the diode, $R_{TH} = 400\Omega \,//\, 600\Omega = 240\Omega$. Also, $V_{TH} = 20V \times 600 / (400 + 600) = 12V$. Thus the Thevenin equivalent is as shown. Since $V_{TH} > 9$ V, current will flow through the diode.



Thevenin Equivalent

$$I_D = \frac{(12 - 9)V}{(200 + 240)\Omega} = \frac{3}{440}\,A = I_{200}$$

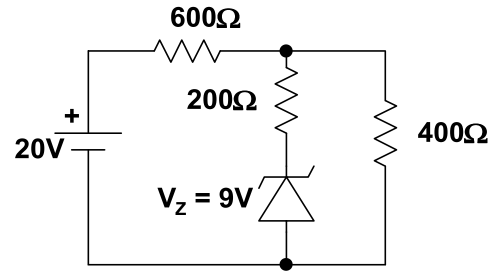
$$V_{200} = 200 \times I_{200} = \frac{600}{440}\,V = \frac{30}{22}\,V$$

$$V_{600} = V_{200} + V_Z = \frac{(30 + 198)}{22}\,V = \frac{57}{11}\,V$$

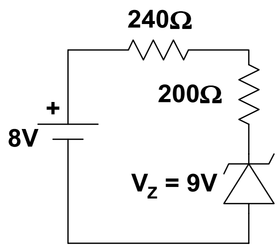
$$I_{600} = \frac{V_{600}}{600} = \frac{57}{6600}\,A$$

$$I_{400} = I_{600} + I_D = \frac{3}{440} + \frac{57}{6600} = \frac{51}{3300}A = 15.45\text{ ma}$$

2. Repeat example 1 with the positions of the 400Ω and 600Ω resistors exchanged.



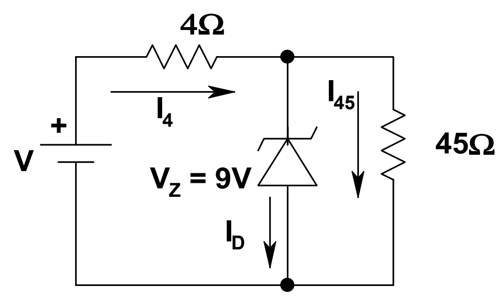
Solution: Proceeding as before, the Thevenin voltage is 8V. This is less than the 9V necessary for reaching V_Z.



Thevenin Equivalent

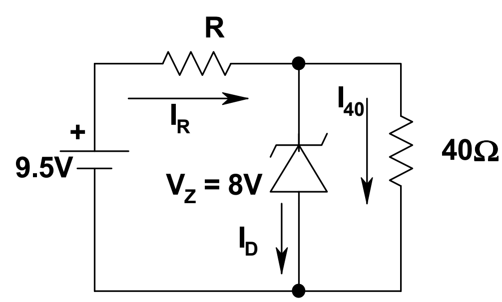
Thus no current flows through the diode and in the center branch. Current in the 600Ω and 400Ω resistors are the same: $\mathbf{I_{400} = I_{600} = 20V / (1000\Omega) = 20}$ **ma.**

3. Calculate the voltage V making $I_D \geq 25$ ma in the circuit shown:



Solution: When I_D = 25 ma, $V_{45} = V_z$ = 9V and I_{45} = 0.200A. By KCL, $I_4 = I_D + I_{45}$ = 0.225A = 225 ma. When 225 ma flows through 4Ω, V_4 = 0.9 V. By KVL, $\mathbf{V = V_4 + V_Z = 0.9V + 9.0V = 9.9V}$. Obviously, if V > 9.9V, I_D > 25 ma (***but, V_Z remains at 9V for all higher values of I_D***). Just as obviously, if V < 9.9V, I_D < 25 ma. In fact, if V < 9.0 V, I_D = 0!!

4. Calculate the value of R making $I_D \geq 30$ ma in the circuit shown.

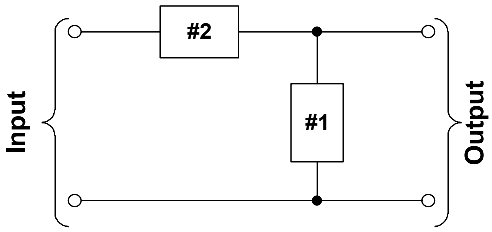


Solution: When I_D = 30 ma, $V_{40} = V_z$ = 8V and I_{40} = 0.200A. By KCL, $I_R = I_D + I_{40}$ = 0.230A = 230 ma. R must be the value that creates V_R = (9.5 - 8.0) V = 1.5 V when 230 ma flows through it. **Thus, R = (1.5V/.23A) = 6.52Ω.**

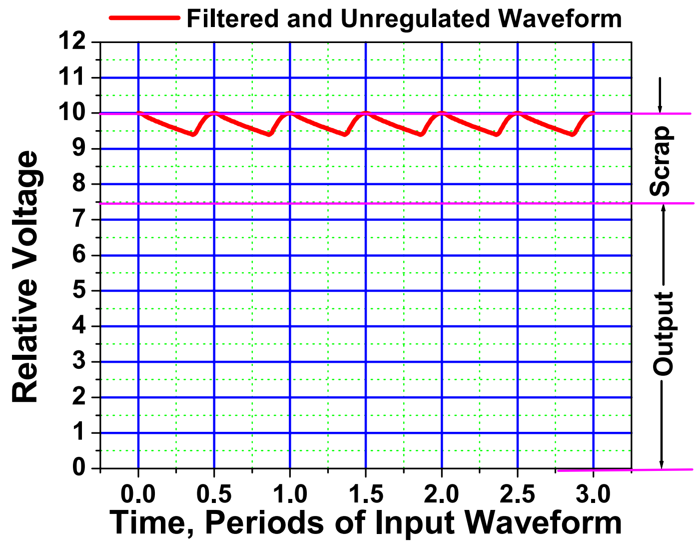
Zener Diode Voltage Regulators

The basic concept of voltage regulators is to divide the voltage into two parts. One part is steady and is used as the output; the other part carries all the variations and is “scrap.” This is equivalent to the operation of smoothing a board, or piece of fabric, by “trimming off” the uneven edges. The graph shows this concept.

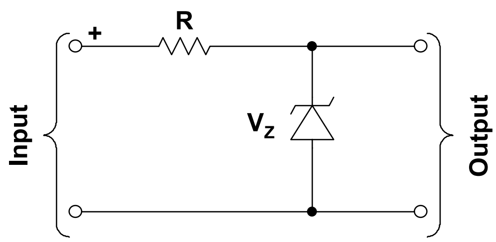
The general circuit for accomplishing this is nothing more that a voltage divider circuit. A conceptual version of the circuit is shown below. The key point is that one element (#1) must have the ability to maintain the voltage across it at a constant level while allowing the unsteady voltage to be developed across the second (#2).



Conceptual Voltage Regulator



The property of a Zener diode, that the Zener voltage remains virtually constant regardless of the current through it, makes it useful for element #1. A resistor can serve as #2. Consequently, a suitable Zener diode-based voltage regulator is:

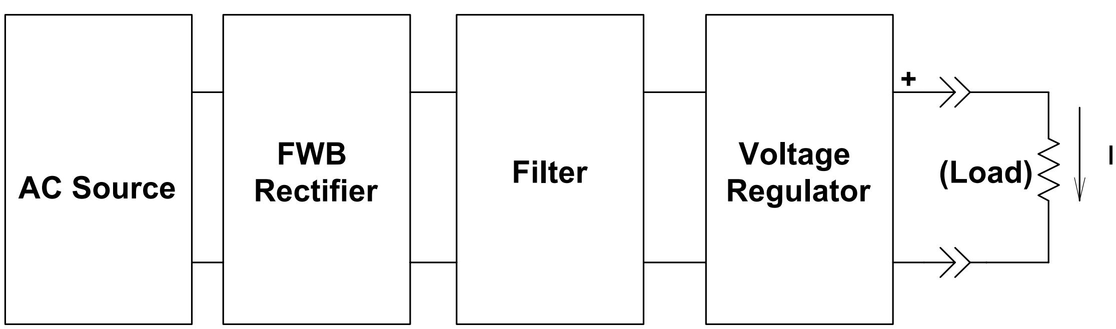


Zener Diode Voltage Regulator

In practice, therefore, ***design*** of a zener diode voltage regulator reduces to calculating a suitable value for the resistor (***R***), and the more practical calculations of the necessary power-handling requirements for the resistor (P_R) and the diode (P_D).

Power Supply Block Diagram

Having now introduced voltage regulators as sections of a power supply, we can update our block diagram to the following:

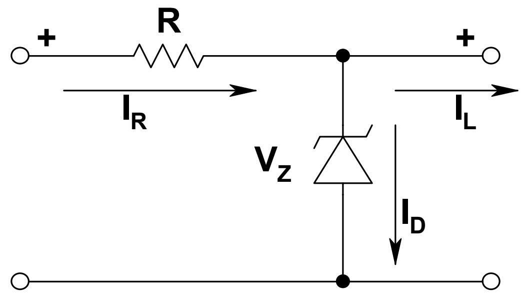


Power Supply, Updated Block Diagram

Example:

Calculate a suitable resistance value, resistor power rating, and diode power rating for a Zener diode regulator as follows:

Have: ***9.5V ≤ V_{in} ≤ 10.0V***;
Want: ***V_{OUT} = 9.0V @ 0 up to 225ma***.
Requirement: ***$I_{D,min}$ = 25ma***



Since $I_R = I_D + I_L$, and we need to ensure availability of ***at least (25 + 225)ma = 250ma*** at all times, we must have the ***minimum value*** of I_R ***no less than*** 250 ma. At the same time, we want the diode voltage to equal V_Z. Thus the voltage across the resistor in general will be $\boldsymbol{V_R = V_{in} - V_Z}$, and the ***minimum current through the resistor will be determined by the minimum value of V_R***. For this case, ***$V_{R,min}$ = 0.5V***. **Together, $V_{R,min}$ and $I_{R,min}$ determine R *through Ohm's law***:

$$\mathbf{R} = \frac{0.5\text{V}}{0.250\text{A}} = \mathbf{2.0}\ \Omega .$$

Since $\boldsymbol{P_R = V_R^2 / R}$ and the "worst case" is when V_R is maximum,

$$\mathbf{P_R} = V_{R,max}^2 \ / \ R = (1.0^2 \ / \ 2.0)\ \text{W} = \mathbf{0.5\ W.}$$

Finally, the diode has no parameter like R, thus P_D must be calculated by the general relation, $P_D = V_D \times I_D$. Although $V_D = V_Z$, and is constant (if we have a suitable value for R), I_D is not constant. The highest possible (worst case) value for I_R occurs when the load is disconnected. In that case, ***all*** the current passing through the resistor is routed to the diode. Therefore,

$$\begin{aligned}\mathbf{P_D} &= V_D \times I_{D,max} = V_Z \times I_{D,max} = V_Z \times I_{R,max} \\ &= (9\text{V}) \times (0.5\text{A}) = \mathbf{4.5\ W.}\end{aligned}$$

Other Consequences of Real Diodes

Voltage Regulator: In the discussions above, we treated the Zener diode as if the Zener voltage were absolutely independent of current through the diode. Of course this isn't ***exactly*** true. In fact, the VI characteristic has large but finite slope. As a consequence, the slope (itself not exactly constant) is characterized by the ***dynamic resistance***, defined as $R_d = \Delta V / \Delta I$, where V and I are in the conduction range, (the inverse of the slope as we presented the characteristic) has a small but non-zero value. Typical values are 2 to 10 Ω. Because the dynamic resistance is not zero, a small amount of ripple will remain following a Zener-diode voltage regulator.

Rectifying Low-level Signals: Some applications require rectifying low-level AC waveforms; for example demodulating an AM radio signal. In these cases, the existence of a threshold for forward conduction means the signal amplitude may be insufficient to attain the threshold. Also in these cases, the curvature of the VI characteristic at the onset of conduction becomes important.