

TUTORIAL PROJECT – ZENER VOLTAGE REGULATOR

This material is an edited extract from an introductory ECE311 experiment that, within the context of semiconductor diode circuits, was intended to reacquaint students with laboratory rules, procedures, and equipment, and course requirements, as well as properties and representative applications of semiconductor diodes. For this contemporary use material associated particularly with the Zener diode is used. The experiment is to be a virtual one, i.e., conducted using computer emulation. Additional technical information to the abbreviated review below is available from texts, notes from earlier courses, articles, as well as consultation with others.

Idealized Diode

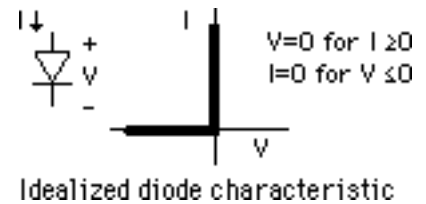
'Real' circuit elements, for example, resistors, capacitors, and inductors are approximations to the idealized circuit elements of the same name valid within certain limitations. An adequate circuit description of the properties of an actual 'resistor' for example, particularly at higher frequencies, involves idealized inductors and idealized capacitors as well as an idealized resistor. Moreover the actual terminal volt-ampere relation may be nonlinear. Idealized circuit elements each isolate a distinct aspect of general circuit behavior, a conceptual separation that is at best only approximated in practice over a limited range of operation. Nevertheless idealized elements in combination can usefully approximate physical circuit behavior. Appreciating and using such approximations is an important part of this experiment.

The idealized diode is an approximation to semiconductor PN junction diode non-bilateral terminal behavior. By definition it is a two terminal device whose terminal properties depend on the direction of current flow through the diode and the polarity of the terminal voltage difference across the diode.

These terminal properties are defined in the drawings to the right.

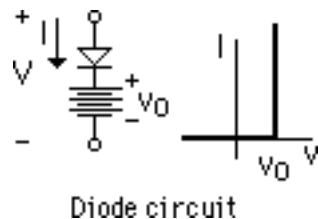
The emphasis on the word 'defined' should be noted carefully. It is important to appreciate that the idealized diode is not a device actually existing in nature, although various real devices can approximate its characteristics. It is a definition of a functional relationship,

represented pictorially by the 'arrow' icon as shown in the figure. For the moment we consider basically only the idealized device, although a circuit involving real devices is considered later.



The diode icon itself may be used to recall polarity conventions for the terminal voltage and current corresponding to the definition above. A non-zero current flows only in the direction suggested by the icon 'arrow'. Unlike a resistor for example, no power is expended in the idealized device by this flow since the diode voltage is zero whenever any current flows. The upper of the algebraic expressions corresponds to the vertical segment of the diode characteristic. In contrast to this 'easy' direction of current flow in 'forward bias' the device is open-circuit for any 'reverse bias' voltage; no diode current flows for $V < 0$. The diode behaves as a sort of switch, open-circuit and preventing current flow in one direction, and short-circuit to allow current to flow in the other direction. Unlike say a mechanical switch the idealized diode is 'opened' or 'closed' simply by virtue of the current and voltage polarity involved. Whether an idealized diode in a particular circuit is forward or reverse-biased is determined by the details of the circuit in which the diode is embedded.

Because the switch-like circuit behavior of the idealized diode does not depend on some sort of externally controlled switching mechanism it can be used to automatically change the effective electrical topology of a circuit. Consider, for example, the circuit drawn to the left, consisting of an idealized diode in series with a DC voltage source.

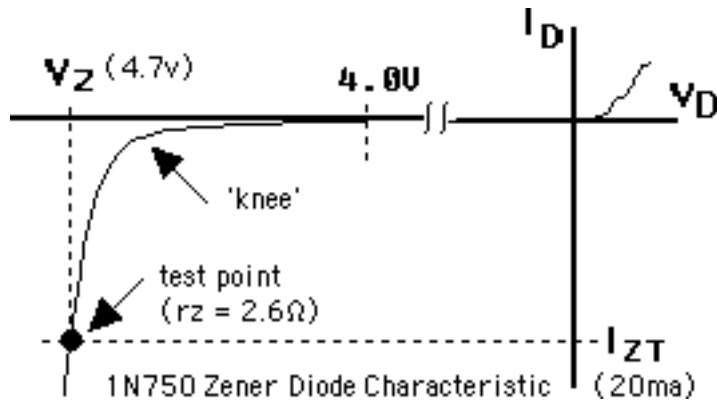


The voltage drop across the diode (in the direction of easy current flow) is $V - V_0$. So long as this voltage difference is not positive the diode is reverse-biased, and the idealized diode property is that no current flows for this condition. If current does flow it must do so in the 'forward' direction, and the voltage drop across the diode, i.e., the difference $V - V_0$, then is zero. The overall volt-ampere

characteristic is drawn besides the circuit diagram. (Incidentally this combination of circuit components provides what might be considered a better approximation to the terminal characteristic of a real diode.)

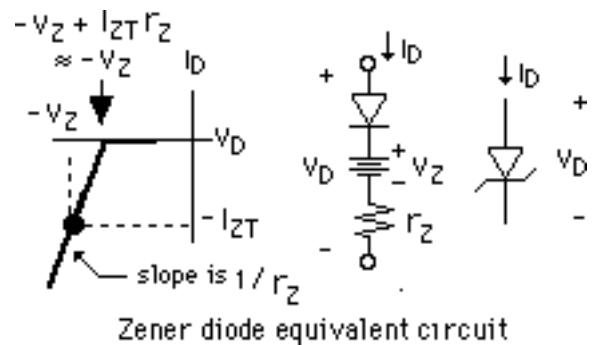
Zener Diode

Ordinarily the reverse-bias blocking action of a PN junction enables only a small 'leakage' current to flow; this corresponds to the zero-current range of the idealized diode characteristic. However if a sufficiently large reverse bias is applied phenomena other than PN junction effects occur. These phenomena enable a reverse current flow sufficiently large to mask the small intrinsic junction current, and the reverse-biased junction is said to operate in 'breakdown'. Note that 'breakdown' here is a reference to the reversible alternate conduction mechanism rather than implying a physical destruction. All diodes exhibit the breakdown phenomena. However diodes intended for operation in 'breakdown' (referred to as Zener diodes) are manufactured and sorted for specific operating characteristics in breakdown. There is a premium for this special handling, and Zener diodes would not ordinarily be used for forward bias operation.



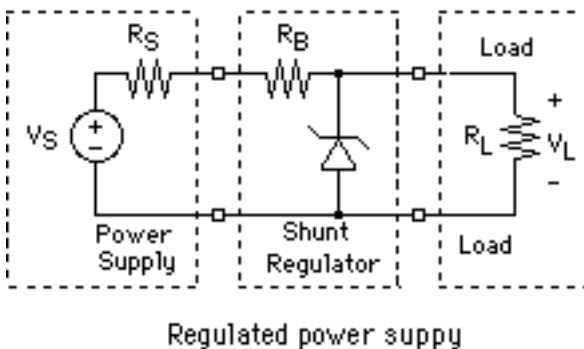
A computer plot of the breakdown characteristic of the 1N750 Zener diode is drawn on the left. The nominal Zener reference voltage of the diode V_Z is the reverse bias voltage at which a manufacturer-specified 'test' current I_{ZT} flows. The inverse of the slope of the diode characteristic at the test point is called the 'dynamic resistance' r_z of the diode and is a parameter noted in the manufacturers' specifications; the slope of the actual diode characteristic does not vary greatly for currents in the range (roughly) between $0.1 I_{ZT}$ and I_{ZT} , a usual range of breakdown operation.

A piecewise linear approximation to the Zener characteristic applicable to analysis of Zener diode operation (i.e., in breakdown and reverse bias) may be used for approximate calculations; one such representation is shown on the right side of the figure, together with an idealized diode equivalent circuit. (Do not confuse the idealized diode used in the model with the Zener diode whose characteristic is being modeled; the actual device characteristic is being approximated over a limited range of operation by a combination of idealized device characteristics. The icon for a Zener diode is drawn on the right side of the figure. Even a simplified device model such as this can provide useful preliminary information about the role and relative importance of circuit components in the circuit performance. Subsequent computer analysis of the circuit (or physical prototype measurements) then can be used refine an initial design. This aspect of the use of the model is illustrated by application to the design of a type of 'shunt' regulator (so-called because the regulating element shunts the load).



Zener Diode Shunt Regulator

An illustrative application of a Zener diode, illustrated by the circuit diagram below, is a 'shunt' voltage



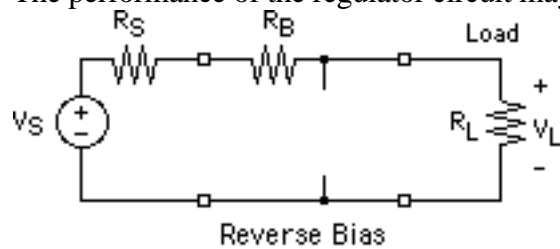
regulator; V_S and R_S represent the Thevenin equivalent circuit as seen looking into the terminals of a DC power supply, and R_B and the Zener diode serve as control devices to regulate the voltage across the load R_L . Absent the regulating elements, i.e. a direct connection between the source and the load, an increase in load current (caused say by reducing R_L) produces a larger 'internal' power supply voltage drop across R_S and consequently a lower supply terminal voltage. This load-voltage variability is measured by the 'regulation' of the power supply, defined formally as the change in terminal

voltage between 'no load' and 'full load' current conditions, divided by the 'no load' voltage. It is essentially a measure of the effect of the internal resistance of the supply on the terminal voltage as the load current changes from one to the other extreme of its specified range of operation.

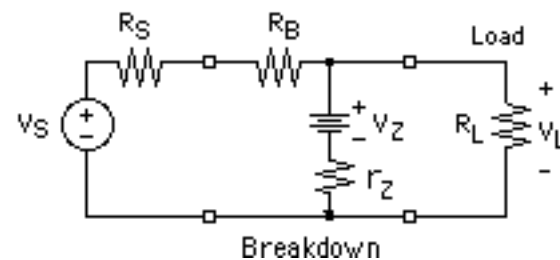
Adding the Zener diode and R_B modifies the load as seen by the supply, i.e., looking out of the intrinsic supply terminals toward the load. The load current consists of the current drawn through R_L plus the added current drawn by the Zener diode. The total load current, from the point of view of the power supply, is larger than what it would be absent the Zener diode and R_B , and represents a 'cost' of the regulation.

To the extent that the voltage drop across the Zener diode is constant the circuit maintains a constant supply current, dividing that current between the Zener diode branch and the actual load R_L . (Actually since the Zener resistance r_z is not zero, the Zener voltage varies somewhat as the diode current varies.) Since the intrinsic power supply itself provides a more or less fixed current, its terminal voltage changes very little. The fixed supply current divides, part to provide the appropriate load current, with the remaining current going through the diode. The Zener diode provides an approximation to a constant voltage source independent of the current it carries, and R_B provides for the necessary voltage drop between the supply voltage and the necessarily lower Zener regulated load voltage.

The performance of the regulator circuit may be estimated by using the idealized approximation for the Zener characteristics. There are two circumstances to consider.



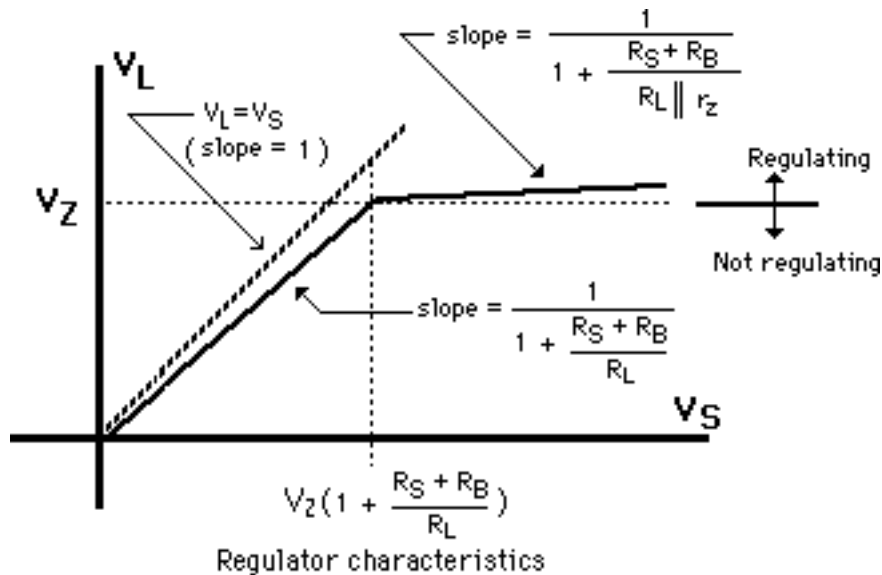
If the diode is not operating in the breakdown region, i.e., it is in the ordinary reverse biased state, it is approximated simply as an open circuit. As illustrated in the upper figure



On the other hand if the diode is in the breakdown stage it acts essentially as a resistance r_z in series with a voltage source V_Z , as illustrated in the lower figure.. Analysis of the approximate circuit is left as an exercise. Note that operation in breakdown requires a reverse voltage of no less than V_Z , and this requirement marks the boundary between the two operating conditions.

The calculated regulating action is indicated in the curves drawn below, obtained by an analysis of the circuit using the piecewise-linear Zener diode approximation as described. For reference a unity slope reference line (dashed) is added to indicate the voltage transfer characteristic of the intrinsic power supply alone, i.e., when the regulating elements are removed so that $V_L=V_S$.

The solid curve describes the circuit with the regulating elements inserted. As soon as the load voltage (voltage across the Zener diode) reaches the Zener breakdown voltage the overall load resistance seen by the supply becomes nearly constant ($= R_B + r_z || R_L$, $R_B + r_z$ assuming $r_z \ll R_L$, as likely would be the case).



Note again implicit qualification that effective regulation depends on operation of the Zener diode in its breakdown region. This is not something that happens automatically; it must be assured as part of the design. There are in fact two conditions that must be met.

For proper regulation the Zener diode must draw enough current to operate sufficiently far into the nearly constant voltage range above the 'knee' of the breakdown characteristic. This must be so even in the extreme situation when the maximum load current has been siphoned off from the supply current, i.e., at the minimum diode current. Hence at full-load current the circuit should be designed for a Zener current of more than (roughly) $0.1 I_{ZT}$. On the other hand when the load draws the minimum current the part of the supply current through the Zener diode should not exceed the rated I_{ZT} . Between these operating requirements, and of course knowing the (nominal) Zener diode voltage, an appropriate value of R_B can be selected. Note that the constraints are in the form of inequalities, and set a maximum and a minimum value for R_B . These are not necessarily the same, and selection of a specific value for R_B involves a design judgment based on other performance considerations.

Zener Regulator Project Statement

The approximate analysis presented above is just that, i.e. approximate. It is at best fortuitous if that analysis predicts precise voltage or current values. On the other hand a certain continuity in nature suggests that even for a simplified circuit model there is a not unreasonable expectation for approximate numerical predictions, and perhaps more importantly for an indication of the relative importance of various circuit parameters on performance. Evaluate this suggestion as you perform the various (virtual) measurements called for.

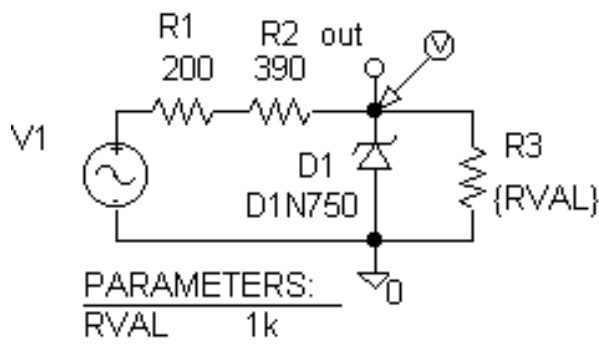
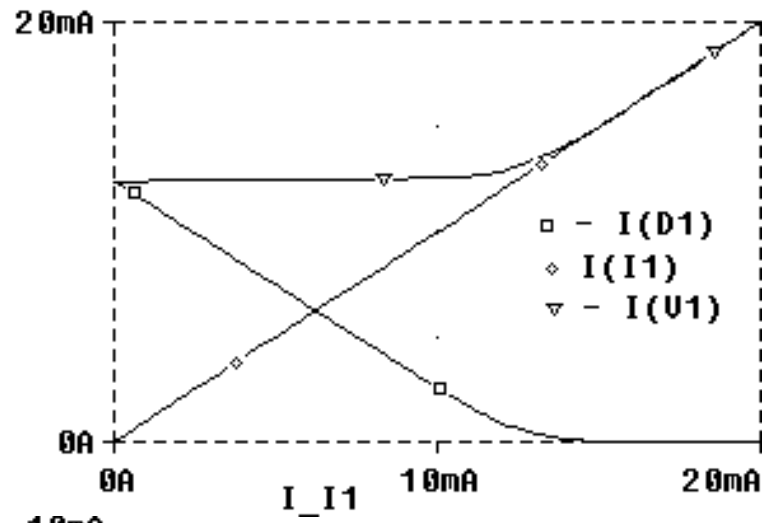
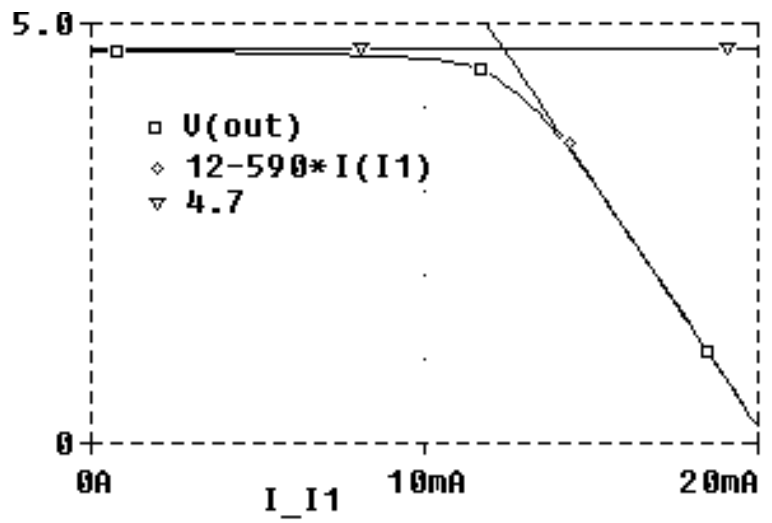
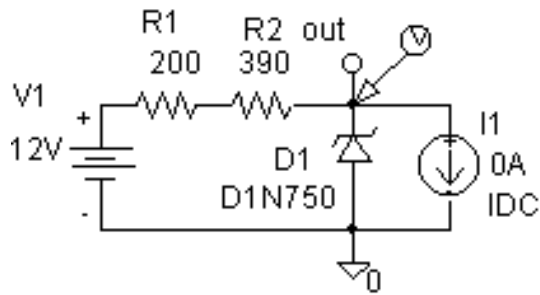
To simulate a relatively poorly regulated intrinsic power supply for purposes of this experiment insert a resistance of 200 Ω in series with a DC source, and consider this resistance to be part of the 'internal' resistance of a poorly regulated supply, i.e., R_S . Set the no-load (open-circuit or Thevenin) supply voltage to 12 volts. PSpice provides a model for a 1N750 Zener diode. The nominal 'test point' breakdown voltage for this Zener diode (read from manufacturer's specifications) is 4.7 volts @ 20 milliamperes; the Zener resistance r_z is 2.6 Ω .

Design a shunt regulator (i.e., in effect specify a standard value for R_B) for load (R_L) currents varying between a maximum of 10 milliampere down to a minimum of 2 milliampere (nominal values).

- a) Relate your selected R_B to the size of the source current for regulated operation; what is the effect expected on using a larger or a smaller value of R_B than specified?

- b) Compute and plot load voltage V_L as a function of load current I_L for a fixed source $V_S = 12\text{v}$, (You may find it convenient to use a DC current source rather than a resistor as a load, and sweep the DC current.). Compare the computed data to anticipated performance; consider both the nature of the variation as well as numerical values. Is the regulation improved over that absent the regulating elements. (How/why did you decide?)
- c) Compute and plot V_L vs. V_S as illustrated above for a (nominal) load current of 5 milliamperes. Compare the computed data to the anticipated (approximate) performance, for example representative slope and breakpoint values.
- d) Replace the DC source by the PSpice part VSIN; set DC and AC values to zero, set the offset voltage to 12V, and specify a 120Hz sine wave with amplitude of 2volts. This provides a source voltage of 12v on which is superimposed a 2v peak 'ripple'. Plot the load voltage for a .TRAN analysis for a load current of (nominally) 5 ma; Compare the output ripple magnitude to that of the source ripple; explain the results obtained.

PSpice output plots



390Ω
1k

