Zener Diode Voltage Regulators

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April 3, 2009

Introduction

A Zener diode is a PN junction that has been specially made to have a reverse voltage breakdown at a specific voltage. Its characteristics are otherwise very similar to common diodes. In breakdown the voltage across the Zener diode is close to constant over a wide range of currents thus making it useful as a shunt voltage regulator.

Characteristics

Figure 1 shows the current versus voltage curve for a Zener diode. Observe the nearly constant voltage in the breakdown region.

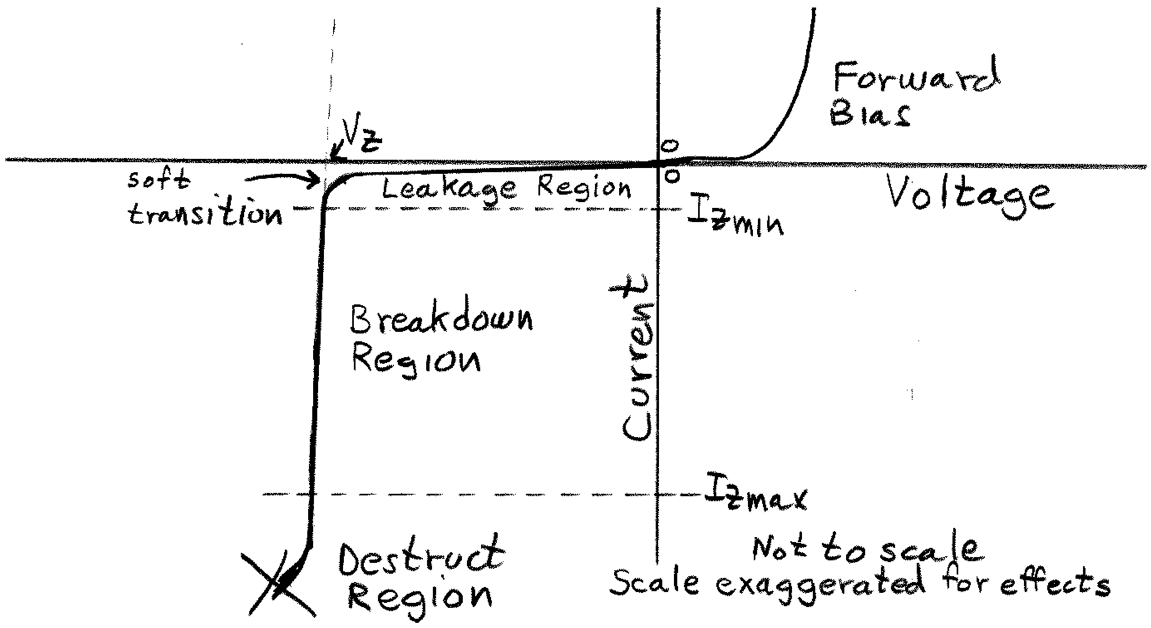

Figure 1: Zener diode characteristics

The forward bias region of a Zener diode is identical to that of a regular diode. The typical forward voltage at room temperature with a current of around 1 mA is around 0.6 volts. In the reverse bias condition the Zener diode is an open circuit and only a small leakage current is flowing as shown on the exaggerated plot. As the breakdown voltage is approached the current will begin to avalanche. The initial transition from leakage to breakdown is soft but then the current rapidly increases as shown on the plot. The voltage across the Zener diode in the breakdown region is very nearly constant with only a small increase in voltage with increasing current. At some high current level the power dissipation of the diode becomes excessive and the part is destroyed. There is a minimum Zener current, I_{Zmin}, that places the operating point in the desired breakdown region and there is a maximum Zener current, I_{Zmax}, at which the power dissipation drives the junction temperature to the maximum allowed (typically in the 125 to 150 C range). Beyond that current and the diode can be damaged or destroyed.

There is no specific value for I_{Zmin} although it is typically taken to be ten percent of I_{Zmax}. It is possible that a lower value could be used particularly at Zener voltages greater than around six. This insures that the diode operating current is in the breakdown region and not in the soft transition region. The ten percent value is also a historical rule-of-thumb for shunt voltage regulators in general. A shunt regulator has to conduct current in order to be in regulation. To prevent the current from going to zero, shunt regulators are often designed so that at the maximum load current there is at least ten percent of that current in the regulator.

Zener diodes are available from about 2.4 to 200 volts typically using the same sequence of values as used for the 5% resistor series – 2.4, 2.7, 3.0 3.3, 3.6, 3.9, 4.3, 4.7, 5.1, 5.6, 6.2, 6.8, 7.5, 8.2, 9.1, 10, 11, 12, 13, 15, 16, 18, 20, 22, 24, etc.

All Zener diodes have a power rating, P_Z. From Watt's law the maximum current is $I_{Zmax} = P_Z / V_Z$. Zener diodes are typically available with power ratings of 0.25, 0.4, 0.5, 1, 2, 3, and 5 watts although other values are available.

The purpose of a voltage regulator is to maintain a constant voltage across a load regardless of variations in the applied input voltage and variations in the load current. A typical Zener diode shunt regulator is shown in Figure 2. The resistor is sized so that when the input voltage is at V_{INmin} and the load current is at I_{Lmax} that the current through the Zener diode is at least I_{Zmin}. Then for all other combinations of input voltage and load current the Zener diode conducts the excess current thus maintaining a constant voltage across the load. The Zener conducts the least current when the load current is the highest and it conducts the most current when the load current is the lowest.

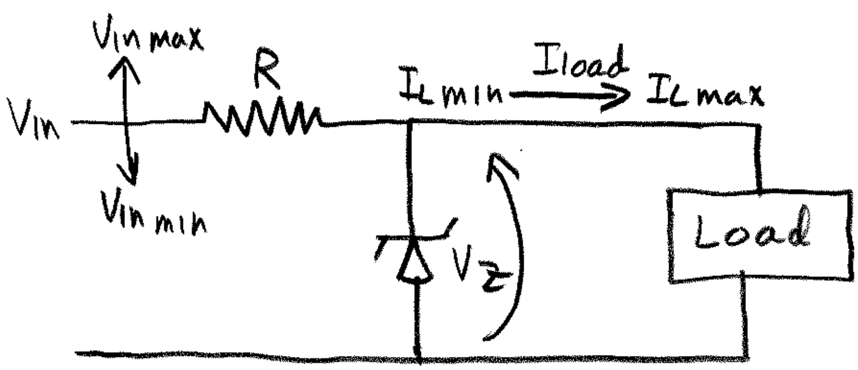

Figure 2: Zener diode shunt regulator

Shunt regulators are normally only used for applications where the load power is not much (no more than a few watts) because under the worst case situation of no load the Zener has to dissipate the full load power. Shunt regulators have an inherent current limiting advantage under load fault conditions because the series resistor limits excess current.

Design

The following data must be known in order to design a voltage regulator using a Zener diode.

V_Z — The desired regulated voltage rounded to the closest available Zener diode standard voltage.

V_{INmin} — The minimum value of the applied input voltage. This must be higher than VZ, preferably at least twenty-five percent higher.

V_{INmax} — The maximum value of the applied input voltage.

I_{Lmin} — The minimum value of load current which is often taken to be zero.

I_{Lmax} — The maximum value of load current.

The design method will use the above data to determine the required power rating of the Zener and the ohmic value and required power rating of the series resistor, R. This is often an iterative process as with many design processes.

1. Estimate the power rating of the Zener by the equation

$$P_{Zest} = \left\{\left[\left(\frac{V_{INmax} - V_Z}{V_{INmin} - V_Z}\right) * (1.1 * I_{Lmax})\right] - I_{Lmin}\right\} * V_Z$$

   Round the result up to the nearest higher available power rating, P_Z. This is only a trial value and may have to be increased depending on the outcome of the following calculations. This estimate comes from substituting $I_{Zmin} = 0.1\ I_{Zmax}$ from step 2 into step 3 and then the resulting unrounded R into step 5.

2. Compute $I_{Zmin} = 0.1 * \text{maximum}(P_Z / V_Z, I_{Lmax})$.

3. Calculate $Rcalc = (V_{INmin} - V_Z) / (I_{Lmax} + I_{Zmin})$.

4. Round Rcalc down (never up) to the nearest standard value, R.

5. Calculate the worst case (i.e. highest) power dissipation in the Zener at the minimum load current (typically zero) as

$$P_{Zmax} = [((V_{INmax} - V_Z) / R) - I_{Lmin}] * V_Z.$$

6. If P_{Zmax} exceeds P_Z then repeat steps 2 through 5 using the next higher available power rating for the Zener voltage.

7. Calculate the maximum power dissipation of R as Rdiss = $(V_{INmax} – V_Z)^2$ / R. Common practice is to roughly double this power value and round up to the nearest standard resistor rating. However, depending on the environment an even higher power rating might be required – that is thermal design which is separate from this article.

Design homework

Determine the power rating of the Zener (using the list of available powers: 0.25, 0.4, 0.5, 1, 2, 3, and 5 watts), the standard ohmic value (5% series), and the power rating of the resistor (0.25, 0.5, 1, 2 watts) for the following designs.

Design Problem					**Answers**		
V_Z	**V_{INmin}**	**V_{INmax}**	**I_{Lmin}**	**I_{Lmax}**	**P_Z**	**R**	**P_R**
5.1	10	12	0	0.05	0.5	75	1
9.1	11.2	12.4	0	0.05	1	33	1
12	15	18	0	0.08	3	27	3
15	19	21	0.05	0.06	1	68	2
12	14.5	15.5	0.03	0.05	1	39	1