# Zener Diode Voltage Regulators

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## 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 5.1 volt Zener diode. Observe the nearly constant voltage in the breakdown region. Also note that the transition from non-conducting to conducting has a soft region. **Important note: Even though the current through the Zener diode is technically negative in the breakdown or regulation region we take that current to be positive in our calculations.** It all works because we also think in terms of the reverse voltage as a positive value. We do this because a plethora of minus signs in our equations just gets in the way.

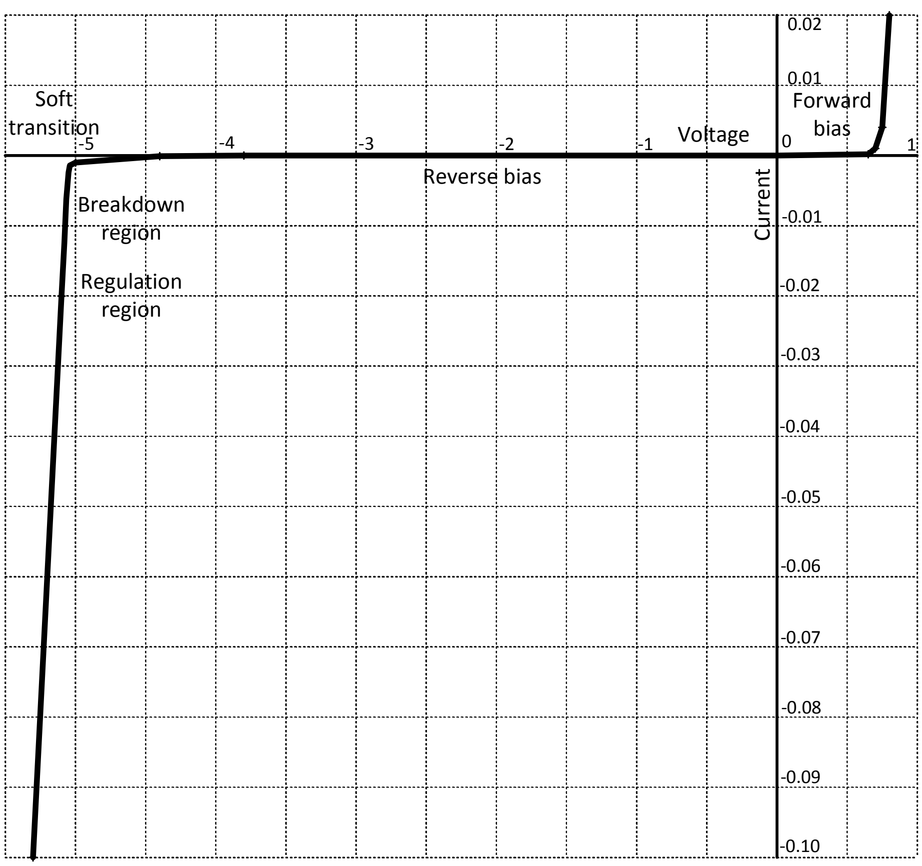


Figure 1: Representative 5.1 volt Zener diode characteristics

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The forward bias region of a Zener diode is identical to that of a regular diode. In the reverse bias condition the Zener diode is an open circuit and there is only a small leakage current in the microampere range. 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 term, breakdown, does not imply destruction. Breakdown only describes a region of operation that we utilize. The voltage across the Zener diode in the breakdown region (also known as the regulation region) is very nearly constant with only a small increase in voltage with increasing current.

## Maximum power dissipation

In the breakdown region the power dissipation of the Zener diode is the product of the voltage across it and the current through it. All Zener diodes have a power rating – a level of power dissipation that drives the junction temperature to the maximum allowed (typically in the 125 to 200 C range). From Watt's law the maximum current is $P_{Zrated}$ divided by $V_Z$. Higher currents will quickly result in temperatures that can damage or destroy the Zener diode. Be aware that the power rating of the Zener diode assumes an ambient temperature of 25 C and that free convection is taking place. For a higher ambient temperature or if convection is limited then the power rating of the Zener diode must be de-rated so that the resulting temperature rise of the power dissipation does not exceed the maximum allowed junction temperature. It would not be unusual to have to de-rate a Zener diode with a specified power dissipation of 1 watt down to less than 0.5 watts for high ambient temperatures and in a convection restricted environment. Forced air can more than make up for convection and reduce the need for de-rating. 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.

## Minimum Zener current

There is a minimum Zener current that places the operating current higher than the soft transition region. The minimum current insures that the diode operating current is in the breakdown region and not in the soft transition region. There is no specific value for this minimum current although it is typically taken to be ten percent of the current for rated power dissipation for Zener voltages less than about 5 volts as lower voltage Zener diodes have an increasingly softer knee. For Zener diodes with a breakdown voltage higher than about 5 where the knee becomes sharper the minimum current could be relaxed to perhaps five percent or less of the maximum rated current. For the example in Figure 1 the current through the Zener diode should always be greater than about 2 mA. That particular diode is a 1N751 which has a maximum power dissipation of 0.5 watts. The maximum current is 0.5/5.1 = 0.098 amperes. The crude ten percent rule suggests that the current always be greater than 9.8 mA – a level that is amply above the absolute minimum. Keep in mind that the ten percent rule is only a guideline and feel free to use lower levels as warranted – but not too low.

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## Zener diode voltages

Zener diodes are available from about 2.4 to 200 volts typically in 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. There are also special values made not part of the 5% sequence.

## Dynamic resistance of a Zener diode

The theoretical ideal voltage regulator has a zero ohm source resistance. That means that the output voltage is completely independent of the load current. A real voltage regulator will have a finite source resistance. In the case of a Zener diode shunt regulator the effective source resistance is

$$R_S = \frac{V_Z@I_{Zhigh} - V_Z@I_{Zlow}}{I_{Zhigh} - I_{Zlow}} \tag{1}$$

where $I_{Zhigh}$ and $I_{Zlow}$ are two distinct current levels within the operating region of the Zener diode. From Figure 1, $V_Z$ @ 100 mA = 5.3 volts and $V_Z$ @ 10 mA = 5.1 volts. Thus, $R_S$ for that Zener diode computes to be 2.9 ohms.

## Voltage regulation

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 diode conducts the least current when the load current is the highest and it conducts the most current when the load current is the lowest.

# Zener Diode Voltage Regulators

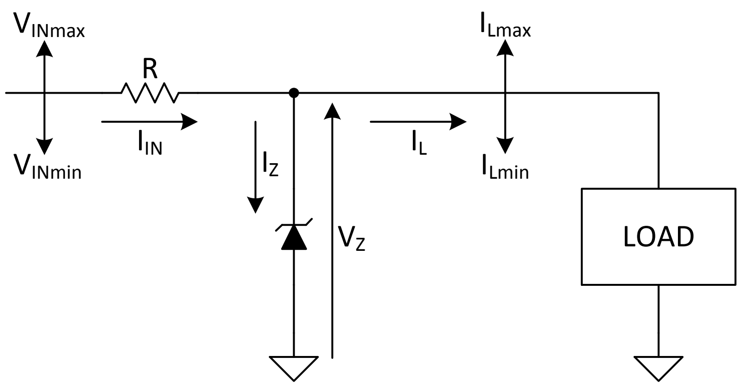


Figure 2: Zener diode shunt regulator

Shunt regulators are normally only used for applications where the load power is not much (often only milliwatts and rarely more than a few hundred milliwatts) because under the worst case situation of no load the Zener has to dissipate the full load power. Shunt regulators are attractive because they are simple and 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 $V_Z$, preferably at least twenty-five percent higher. |
| $V_{INmax}$ | The maximum value of the applied input voltage. Generally this should not much more than about twice VZ so that required power dissipations are not excessive. |
| $I_{Lmin}$ | The minimum value of load current which is often taken to be zero. |
| $I_{Lmax}$ | The maximum value of load current. |

The two things that must be determined using the design process are the resistance for R and the minimum required power rating, $P_{Z\_rated}$, of the Zener diode. We can make two observations about the input current, $I_{IN}$, from the input voltage, $V_{IN}$.

# Zener Diode Voltage Regulators

$$I_{IN} = \frac{V_{IN} - V_Z}{R} \tag{2}$$

$$I_{IN} = I_Z + I_L \tag{3}$$

The minimum $I_{IN}$ occurs at the minimum input voltage, $V_{INmin}$. The resistor must be small enough so that the minimum required current through the Zener diode exists when the load current is at the maximum. Otherwise the output voltage will drop out of regulation.

For any shunt regulator it is standard practice that the minimum shunt current is ten percent of the maximum load current. This is because the shunt element must be sinking current in order to be functioning. Historically, ten percent of the maximum load current has worked well. However, there is also a minimum current through the shunt element for it to regulate at all. In the case of Zener diodes the minimum current must be higher than the soft transition knee because the regulation region does not begin until the current versus voltage curve is steep vertically. So we have two equations for the minimum shunt current noting that the value of 10 in Equation 5 could be increased to perhaps 20 or more for Zener diodes with a breakdown voltage higher than about 5.

$$I_{Zmin} = I_{Lmax}/10 \tag{4}$$

$$I_{Zmin} = \frac{P_{Z\_rated}}{10V_Z} \tag{5}$$

However, at this point we do not yet know what $P_{Z\_rated}$ is. There is only a small finite set of possible values for $P_{Z\_rated}$ (typical values are 0.1, 0.25, 0.4, 0.5, 1, 2, 3, and 5 watts although other values exist). Since our goal is to determine the smallest required rating we will start with perhaps 0.1 watts and after checking the design if that rating turns out to be too small we will try the next higher power rating repeating the process until it works. So step 1 of the design process is to evaluate Equations 4 and 5 using an assumed value for $P_{Z\_rated}$ and choose the larger result.

For step 2 of the design process we calculate the required resistor using the result of step 1. We always round the result down to the nearest lower standard value.

$$R = \frac{V_{INmin} - V_Z}{I_{Lmax} + I_{Zmin}} \tag{6}$$

For step 3 we calculate the maximum power dissipation of the Zener diode. The worst case situation occurs when $V_{IN}$ is at the maximum value and the load current is at the minimum value as that results in the highest current through the Zener diode. Expressed as an equation the maximum Zener diode current is

$$I_{Zmax} = \frac{V_{INmax} - V_Z}{R} - I_{Lmin} \tag{7}$$

$$P_{Zmax} = V_Z I_{Zmax} \tag{8}$$

If $P_{Zmax}$ is greater than $P_{Z\_rated}$ then we iterate from Equation 5 using the next higher power rated Zener until $P_{Zmax}$ is less than $P_{Z\_rated}$. Design is often an iterative process. However, if $P_{Zmax}$ is only a small amount less than $P_{Z\_rated}$ then we will still choose the next higher rating and iterate one more time as we might also have a design criteria not to stress the components to the absolute maximum in order that design have a long service life without failure. This is particularly important if the Zener could be operated in ambient temperatures well above 25 C because the true $P_{Z\_rated}$ has to be scaled down (i.e. de-rated) from the data sheet $P_{Z\_rated}$ value which assumes an ambient temperature of 25 C . We round the result up to the nearest higher standard power rating and perform the preceding calculations.

Once we know the required power rating of the Zener diode and have determined the required resistor we next calculate the worst case power dissipation of the resistor.

$$P_{Rmax} = \frac{(V_{INmax} - V_Z)^2}{R} \tag{9}$$

We must use a resistor with at least the next higher power rating than computed using Equation 9. A common practice is to first double $P_{Rmax}$ and then round up as this provides some stress margin – but in ambient temperatures well above 25 C this simplistic margin may not be enough. True thermal design is always necessary.

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## A faster method to determine the required $P_{Z\_rated}$ value

We would like to have an equation that directly tells us the required minimum power rating of the Zener diode so we do not have to perform the above iteration.  The following approximate equation is derived from the iterative method and provides an estimate of the required power rating of the Zener diode.  The estimate might be one rating low in some cases so be prepared to perform one additional iteration if required. The concept of not necessarily designing to the stress limit of the part still applies.

$$P_{Z\_rated\_est} = \left[\left(\frac{V_{INmax} - V_Z}{V_{INmin} - V_Z}\right)(1.1 I_{Lmax}) - I_{Lmin}\right] V_Z \tag{10}$$

Equation 10 provides several insights into what drives the required power rating.  A wide spread of $V_{INmax}$ to $V_{INmin}$ will lead to higher power dissipation.  Also, if $V_{INmin}$ is not much above $V_Z$ then the power dissipation could become high.  Higher load currents and a wide spread between $I_{Lmax}$ and $I_{Lmin}$ will also lead to higher power dissipation.

## Step down series connection

When there is a need to step a regulated voltage such as +15 down to +12 then a neat method is to use a 3.0 volt Zener diode in series as shown in Figure 3.  This concept is applicable if the higher voltage is already regulated and precise regulation of the lower voltage is not required.  In some cases a resistor might need to be added to insure the minimum current through the Zener diode.

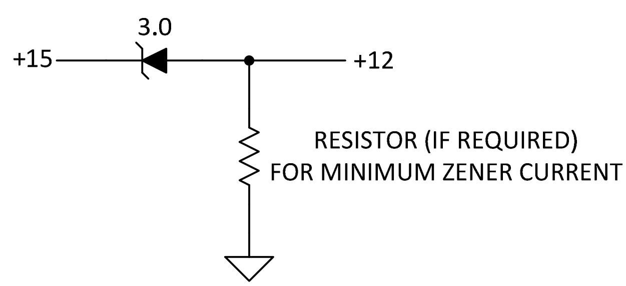


Figure 3: Step down series connection

# Zener Diode Voltage Regulators

## Using a transistor to create a high power shunt regulator

Rather than using a high powered Zener diode, a power transistor capable of dissipating significant power when thermally coupled to a large heat sink can be connected as shown in Figure 4 so that only a low-power Zener diode is needed. The output voltage is around 0.65 volts higher than the Zener voltage because the series connection of the base-emitter junction of the transistor.

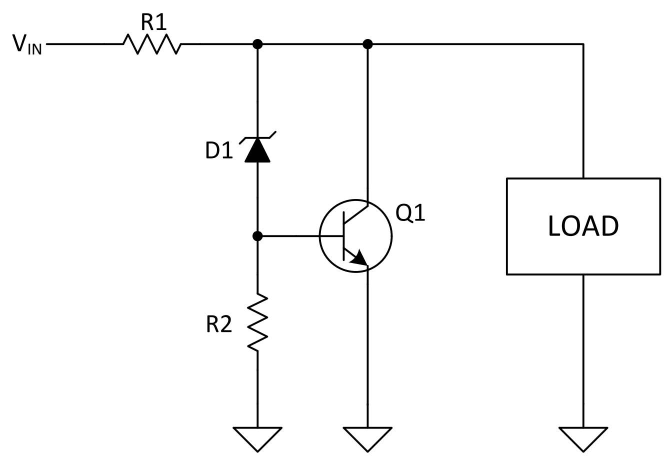


Figure 4: Use of a transistor for high current shunt regulator

The design process is similar to previous process except that the maximum required current through the Zener diode is reduced by the beta of the transistor. $R_2$ sets the minimum current through the Zener diode and is nominally 0.65 / $I_{Zmin}$. $R_1$ is calculated the usual way.

## Negative voltage regulator

A negative voltage regulator is shown in Figure 5. The math and design method is identical to that for positive voltages. All of the signs of voltage and current are negative. The design for this is often solved as if it were a positive voltage just to avoid pesky minus signs.

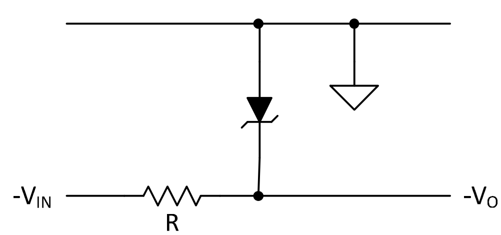


Figure 5: Negative voltage regulator

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## Design homework

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

| **Design Problem** | | | | | **Answers** | | |
|---|---|---|---|---|---|---|---|
| **$V_Z$** | **$V_{INmin}$** | **$V_{INmax}$** | **$I_{Lmin}$** | **$I_{Lmax}$** | **$P_Z$** | **R** | **$P_R$** |
| 4.7 | 7.6 | 9.3 | 0 | 0.015 | 0.25 | 130 | 0.163 |
| 5.1 | 12 | 12 | 0 | 0.05 | 0.5 | 110 | 0.433 |
| 5.1 | 8 | 12 | 0 | 0.25 | 5 | 8.2 | 5.8 |
| 9.1 | 12 | 15 | 0.03 | 0.12 | 3 | 18 | 1.9 |
| 12 | 15 | 18 | 0.02 | 0.06 | 2 | 36 | 1.0 |
| 15 | 23 | 225 | 0.01 | 0.04 | 1 | 160 | 0.788 |