Voltage Regulation

We've come a long way from an AC circuit with no DC to a DC signal with some ripple on it, which we can control to some extent through our choice of rectifying circuit and filtering capacitor.

However, our circuit's DC output is still dependent on the peak voltage of the input signal, for which we will need what's called "Line Regulation" -- making the output DC less dependent on changes in the Line voltage. It's also dependent on the current drawn through the attached load, for which we will need what's called "Load Regulation" -- making the output DC less dependent on changes in the load resistance.

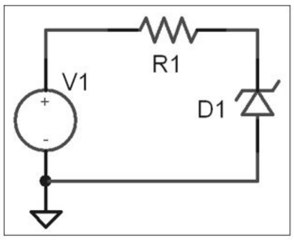
Regulation refers simply to the attempt to maintain a constant output regardless of changes in the source or the load.

Most regulator circuits employ Zener Diodes in one way or another to help them maintain a constant output voltage.

Zener Diode

The Zener Diode is designed to have a predictable reverse breakdown voltage, and is therefore typically installed in reverse bias in a circuit.

Using Multisim, build the following circuit, and answer the questions that follow. use a 3.3 kΩ resistor and a 1N4738A Zener diode. Use a "DC_INTERACTIVE_VOLTAGE" for V_1, as you will be changing its value. Place an "A/V" probe on the node between the resistor and the diode.



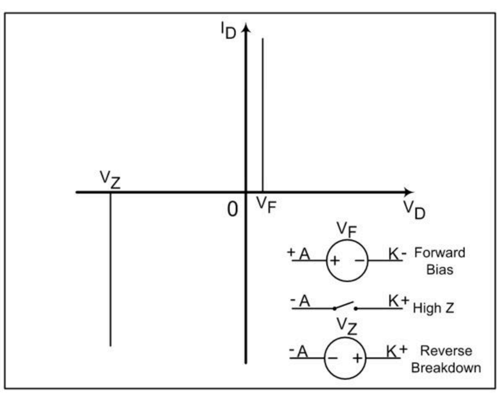
Set the input voltage to the values shown in the table, and record the voltages and currents observed at the cathode of the diode.

V_1, V	V_D, V	I, mA
-0.35	-0.35	0
-3.0	-0.5	-0.758
5.0	5	0
15.0	8.2	2.06

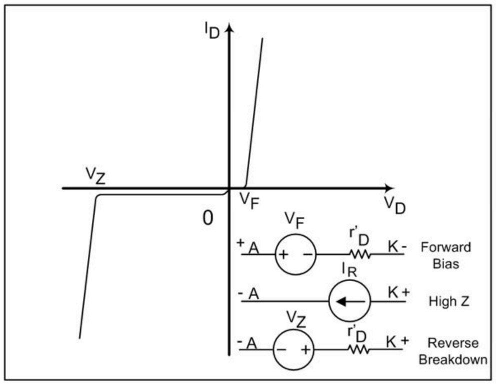
Notice that the diode establishes constant voltages in both the forward and reverse biasing configurations.

Zener Diode Models

The Practical Zener Diode Model says that once either the forward or reverse breakdown voltages have been exceeded, the Zener Diode becomes a constant voltage source regardless of other conditions in the circuit. In between those two voltages, it behaves as an open switch.



The Complete Zener Diode Model includes a fairly significant difference -- that when the diode conducts in either direction, its internal resistance will produce a slight change in voltage, dependent upon the current.



Unfortunately, since power supplies tend to be high current devices, this change in voltage is often significant when Zeners are employed.

Question: Go to the datasheet link below and locate the 1N4733A Zener diode to answer the questions that follow.

Zener Diode Datasheet (https://datasheetspdf.com/pdf-file/134169/DcComponents/1N4735A/1)

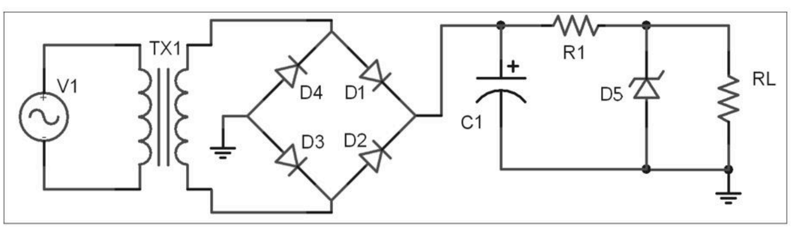
1. What is the reverse breakdown voltage for the 1N4733A (Vz) 5.1 V
2. What current is this reverse breakdown voltage measured at? 49 mA
3. What is the internal resistance of this Zener diode (Z_{ZT})? 7 Ω
4. If the current through the Zener is 250 mA, what is the Zener diode reverse voltage, using the Complete Model?

   6.85 V

Clearly, this Zener diode isn't capable of holding the "regulated" voltage at its reverse breakdown value when a lot of current is drawn through it.

Here's a typical Zener diode-regulated circuit. Since you're not likely to use a circuit like this, we won't spend too much time on the design of it. Instead, we'll work through it as an instructional exercise, from which you should learn how a Zener regulator works and what its limitations are, while reinforcing some of the electrical and electronic concepts you've learned so far.

For this circuit, V1 is 115 VAC, the transformer turns ratio is 16:1, the rectifier diode drops are 0.7 V, C1 is 470 μF, R1 is 39 Ω, D5 is a 1N4733A, and RL is never smaller than 100 Ω.



As usual, we need to work our way through the transformer and rectifier:

- First, determine the peak voltage at the output of the rectifier:
  - start with converting the AC supply from RMS to peak: $V_1 = 115\ V_{RMS} \cdot \sqrt{2}$=162.6 V_p
  - next, determine the voltage at the secondary using the turns ratio: 162.6 V_p/16 = 10.2 V_p
  - finally, subtract two diode voltage drops from the positive peak, since there are always two diodes conducting at at time: V_{rect} = 10.2 V_p - 2(0.7 V) = +8.76 V_p
- Since the load resistor, R_L is in parallel with the Zener diode, they have the same voltage across them; so when the Zener is conducting, the voltage across $R_L = V_Z$. Using the Practical model of the Zener, we conclude that V_{RL} = 5.1 V_{DC}.
- The current through the load, using this voltage, can be predicted using Ohm's Law. The worst case current will be determined using the minimum value of the load resistance. $I_L = V_{RL}/R_L$ = 5.1 V_{DC}/100 Ω = 51 mA_{DC}.
- Let's work back through the circuit. The voltage drop across R_1 (a current-limiting resistor that protects the Zener diode) will be, at the peak of the rectifier cycle, 8.76 V_p - 5.1 V_{DC} = 3.66 V_p

- Using the peak voltage across the current-limiting resistor, we can determine the peak current drawn from the rectifier: $I_T = \Delta V_{R1}/R_1$ = 3.66 V_p/39 Ω = 94.0 mA_p. (You may get a slightly different answer if you use the rounded values above rather than keeping the values on your calculator.)
- Any current in excess of the load current must go through the Zener diode, since there are two parallel current paths. So, the current through the Zener diode is $I_Z = I_T - I_L$ = 94.0 mA_p - 51 mA_{DC} = 43.0 mA_p.
- Now, let's use the Complete model of the diode to determine the actual voltage across the Zener (and the load resistor) at the peak of the regulator's cycle: $V_D = V_Z+I_Z*Z_{ZT}$ = 5.1 V + 43.0 mA_p*7.0 Ω = 5.40 V_{DC}. That's a bit disturbing, as we're using the Zener to "regulate" the voltage at 5.1 V_{DC}. More on that later.
- Let's also determine what voltage would be expected across the Zener if the load resistor was completely removed (i.e. no load attached). $V_D = V_Z+I_Z*Z_{ZT}$ = 5.1 V + 94.0 mA_p*7.0 Ω = 5.76 V_{DC}.

If you think about it, the last two results could get us going on an endless loop of refinements, because the load voltage is no longer what we predicted with the Practical model, so the current is wrong so the load voltage is wrong so the current is wrong .... However, we won't do any iterations on the calculation, because we've based our calculations on some fairly variable values already, such at the diode voltage drops and the supply line voltage.

The formal term for the effect on the output voltage of changing the resistance of the load is ***Load Regulation***. A good voltage regulator will not be affected seriously by the load applied. This means that the Zener regulator we're analyzing does not have good Load Regulation, since it changes from 5.76 V_{DC} when not loaded to 5.40 V_{DC} when typically loaded; theoretically, it could be loaded sufficiently to drop the regulated voltage to 5.1 V_{DC} before it quits regulating at all, so its output could vary by about 0.66 V in response to load changes.

While we're at it, the output voltage would also be affected if the line voltage changed: an increase in line voltage would mean an increase in the peak voltage presented to the current-limiting resistor, which in turn would mean a higher total current, more of which would go through the Zener, resulting in a higher output voltage. The formal term for the effect on the output voltage of changing the supply voltage is ***Line Regulation***. We won't do an analysis of this for our circuit, but suffice it to say that the Zener regulator does not have very good Line regulation performance, either.

Also, it should be apparent that, as the input voltage swings up and down due to its ripple, the output voltage will also swing up and down a little bit, but much less than the input. The measure of the reduction of ripple in a regulator circuit is referred to as ***Ripple Rejection***. Since most regulators significantly reduce the amount of ripple in a signal, the ripple rejection is usually stated in decibels.

$$RR = 20\ \log\left(\frac{V_{r(in)}}{V_{r(out)}}\right)$$

- To do a worst-case analysis of the ripple rejection of the unregulated input to the regulator, we'll use the peak values from our previous calculation.
  - Using the peak total current, we can determine the worst case ripple voltage at the output of the rectifier using $V_r = \frac{I_L T}{C}$ =94.0 mA_p*(1/120 Hz)/470 μF = 1.67 $V_{p\text{-}p}$.
- To determine the output ripple, we've already calculated the voltage expected when the input signal is at its maximum point: 5.40 V. Now we need to calculate the minimum so we can subtract it from the maximum to get the peak-to-peak output ripple.
  - The minimum value for the signal out of the regulator is $V_{min} = V_{max} - V_r$ = 8.76 V_p - 1.67 $V_{p\text{-}p}$ = 7.10 V
  - From this, we can determine the current through the current-limiting resistor: I_{min} = (7.10 V - 5.1 V)/39 Ω = 51.3 mA
  - The current through the Zener diode would be this minimum total current minus the load current, or 51.3 mA - 51.0 mA = 0.3 mA.
  - Using the Complete model of the Zener diode, we can determine that the output voltage at this minimum point would be 5.1 V + 0.3 mA * 7 Ω = 5.10 V (essentially the Zener voltage, since the current is so small).
  - So, the output ripple would be 5.40 V - 5.10 V = 0.3 $V_{p\text{-}p}$
- Finally, we can do a Ripple Rejection calculation: RR=20log(1.67 $V_{p\text{-}p}$/0.3 $V_{p\text{-}p}$) = 14.9 dB

Since most regulators have Ripple Rejection values of over 50 dB, this is not a great regulator from a Ripple Rejection point of view, either.

Much more important than the variation in output voltage is the power wasted by this circuit.

16. How much "useful" power is dissipated by the 100 Ω load? 260 mW

17. At the peak of the rectifier signal, how much power does this entire circuit dissipate? 822 mW

18. At the peak, what is the efficiency of this circuit? 31.6 %

Clearly, a circuit that wastes two-thirds of the power it consumes is not a very good circuit. This circuit is wasteful because it "shunts" whatever current is not needed through the Zener diode in order to maintain the desired voltage across the load, and is therefore referred to as a **Shunt Regulator**, or parallel regulator.

The points of this exercise were to introduce the concept of regulation, provide you some familiarity with the Zener diode, and to give you an example of a "quick and dirty" regulator circuit you could use if your circuit requirements in a particular project aren't too rigid. You won't be asked to build or analyze a Zener Regulator again in this course. That's because there are much better (and easier) ways to regulate voltages in an electronic circuit.

Integrated Circuit Regulators

Voltage regulation is required for practically all electronic circuits. Many devices have a single DC power supply, then regulate that down to the various voltages required by different parts of the circuit. Our microcontroller development kit, for example, uses an unregulated +12 V supply, and we create +10 VDC, -10 VDC, +5.120 VDC, +5 VDC, +3.3 VDC, and +2.5 VDC from it to drive the various chips installed on the board. Fortunately, there are commercially-available Integrated Circuit Regulators to handle all of these required voltages.

Linear Regulators and Switching Regulators

Linear Regulators are simple devices to use, typically available as three-pin devices and requiring no external components other than filtering capacitors. However, as with most simple things, these are limited in their application. Linear Regulators can only reduce the available voltage -- they can't step it up to a higher voltage; and Linear Regulators cannot invert the voltage -- a positive Linear Regulator can only produce a positive output from a positive input, and a negative Linear Regulator can only produce a negative output from a negative input.

Switching Regulators are more complex, requiring external components -- typically a Schottky Diode, an inductor, two feedback resistors, and a frequency setting capacitor, in addition to filtering capacitors at the input and the output. However, by switching a current on and off through an inductor, Switching Regulators can be designed to it all: drop the voltage, increase the voltage, and invert the voltage. In addition, Switching Regulators are more efficient than Linear Regulators, and rarely need heatsinks for typical small applications.

Linear Regulators

Linear Regulators, unlike the Zener Diode Shunt Regulator, are Series Regulators -- they operate by limiting the current through the load to maintain a constant output voltage. If no load is attached, no current is required, so the regulator draws essentially no appreciable current. When a load is attached, current is supplied as needed. Power lost when using a Linear Regulator is due to the voltage drop across the regulator, which behaves like a variable resistor to control the current. Therefore, the bigger the difference between the input unregulated voltage and the output regulated voltage, the greater the power dissipated by the regulator as heat. Also, the greater the current through the regulator, the greater the power dissipated as heat.

19. A Linear Regulator is being used to produce +5 VDC from +12 VDC. How much power is dissipated by the regulator if the current drawn is 500 mA? 3.5 W ... if the current drawn is 20 mA? 140 mW.
20. How much power would be dissipated by the same Linear Regulator, producing 500 mA of current, if it was using +8 VDC at its input instead of +12 V? 1.5 W

Very often, Linear Regulators require heatsinks to prevent them from burning out or from causing heat damage to other parts of a piece of equipment. The manufacturer's specification sheet provides information that can be used in determining the heat sink requirements.