# Aim

To construct a zener diode voltage regulator and measure its line and load regulation.

# Apparatus

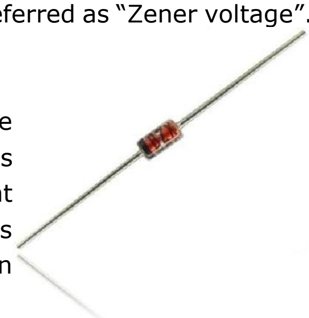
Zener diode, resistor, variable DC power supply, milliammeter, voltmeter, Rheostat  and wire.

# Theory

The Zener diode is like a general-purpose signal diode. When biased in the forward direction it behaves just like a normal signal diode, but when a reverse voltage is applied to it, the voltage remains constant for a wide range of currents.

*Avalanche Breakdown*: There is a limit for the reverse voltage. Reverse voltage can increase until the diode breakdown voltage reaches. This point is called *Avalanche Breakdown* region. At this stage maximum current will flow through the zener diode. This breakdown point is referred as "Zener voltage".

**Fig 1:** Zener diode



The Zener Diode is used in its "reverse bias". From the I-V Characteristics curve we can study that the zener diode has a region in its reverse bias characteristics of almost a constant negative voltage regardless of the value of the current flowing through the diode and remains nearly constant even with large changes in current as long as the zener diodes current remains between the breakdown current $I_{Z(min)}$ and the maximum current rating $I_{Z(max)}$.

This ability to control itself can be used to great effect to regulate or stabilise a voltage source against supply or load variations. The fact that the voltage across the diode in the breakdown region is almost constant turns out to be an important application of the zener diode as a voltage regulator

## Characteristics

Figure 2 shows the current versus voltage curve for a Zener diode. Observe the nearly constant voltage in the breakdown region.

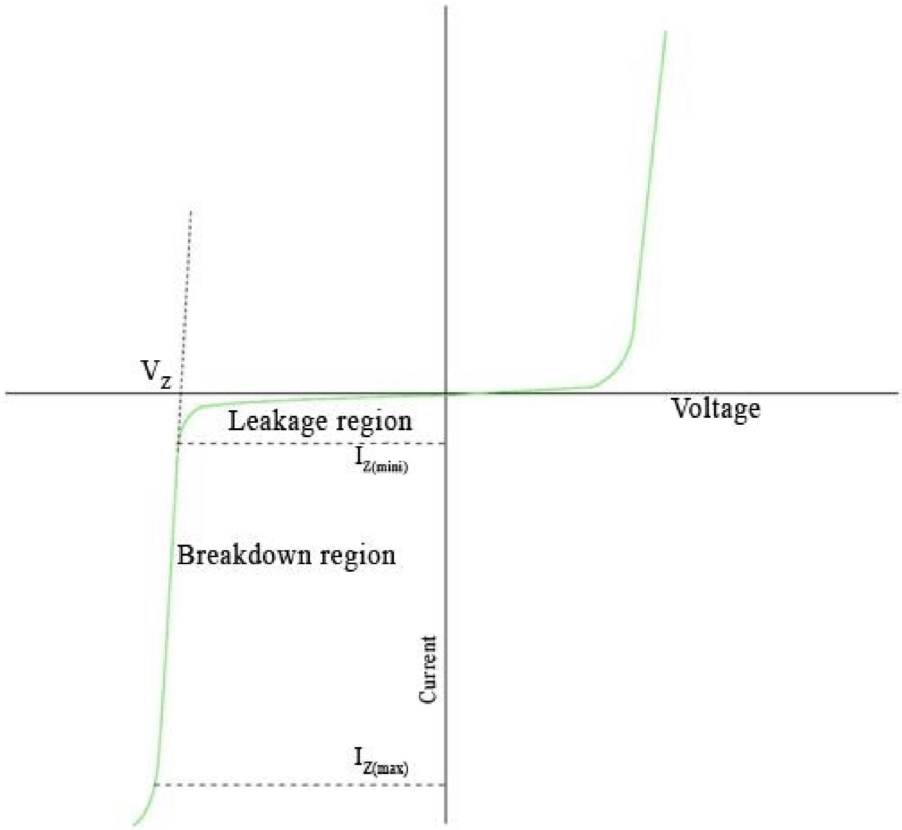



**Fig 2:** Zener diode characteristic curve

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, $I_{z(min)}$, that places the operating point in the desired breakdown. There is a maximum Zener current, $I_{z(max)}$, at which the power dissipation drives the junction temperature to the maximum allowed. Beyond that current the diode can be damaged.

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, Pz. From Watt's law the maximum current is $I_{Z(MAX)}=P_Z / V_Z$. 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.

## Zener Diode as Voltage Regulators

The function of a regulator is to provide a constant output voltage to a load connected in parallel with it in spite of the ripples in the supply voltage or the variation in the load current and the zener diode will continue to regulate the voltage until the diodes current falls below the minimum $I_{Z(min)}$ value in the reverse breakdown region. It permits current to flow in the forward direction as normal, but will also allow it to flow in the reverse direction when the voltage is above a certain value - the breakdown voltage known as the Zener voltage. The Zener diode 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.

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 3. The resistor is selected so that when the input voltage is at $V_{IN(min)}$ and the load current is at $I_{L(max)}$ that the current through the Zener diode is at least $I_{z(min)}$. 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.

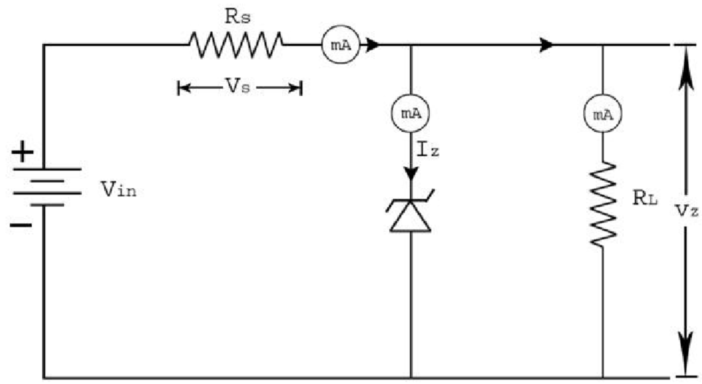



**Fig 3**: Zener diode shunt regulator

If there is no load resistance, shunt regulators can be used to dissipate total power through the series resistance and the Zener diode. Shunt regulators have an inherent current limiting advantage under load fault conditions because the series resistor limits excess current.

A zener diode of break down voltage $V_z$ is reverse connected to an input voltage source $V_i$ across a load resistance $R_L$ and a series resistor $R_S$. The voltage across the zener will remain steady at its break down voltage $V_Z$ for all the values of zener current $I_Z$ as long as the current remains in the break down region. Hence a regulated DC output voltage $V_0 = V_Z$ is obtained across RL, whenever the input voltage remains within a minimum and maximum voltage.

Basically there are two type of regulations such as:

## a) Line Regulation

In this type of regulation, series resistance and load resistance are fixed, only input voltage is changing. Output voltage remains the same as long as the input voltage is maintained above a minimum value.

Percentage of line regulation can be calculated by = $\frac{\Delta V_0}{\Delta V_{IN}} * 100$

where $V_0$ is the output voltage and $V_{IN}$ is the input voltage and $\Delta V_0$ is the change in output voltage for a particular change in input voltage $\Delta V_{IN}$.

## b) Load Regulation

In this type of regulation, input voltage is fixed and the load resistance is varying. Output volt remains same, as long as the load resistance is maintained above a minimum value.

Percentage of load regulation = $\left[\frac{V_{NL}-V_{FL}}{V_{NL}}\right]*100$

where $V_{NL}$ is the null load resistor voltage (ie. remove the load resistance and measure the voltage across the Zener Diode) and $V_{FL}$ is the full load resistor voltage

## Design a Voltage Regulator

When selecting the zener diode, be sure that its maximum power rating is not exceeded.

$I_{max}$ Maximum current for Zener diode

$$I_{max} = \frac{Power}{Zener\ voltage}$$

$V_Z$ Zener Diode standard voltage

$V_{in}$ Input voltage(it is known)

$V_s$ Voltage across series resistance

$V_L$ Voltage across the load resistance

$I_S$ Current passing through the series resistance

$I_Z$ Current passing through the Zener diode

$I_L$ Current passing through the load resistance

**Calculating voltage and current**

The total current drawn from the source is the same as that through the series resistor

$$I_S = \frac{V_S}{R_S}$$

The current through the load resistor is

$$I_L = \frac{V_L}{R_L}$$

and the zener diode current is

$$I_Z = I_S - I_L$$

If the voltage source is greater than Vz

$V_s = V_{in} - V_L$ and $V_L = V_Z$

If the voltage source is less than Vz

$$V_s = \frac{R_S * V_{in}}{(R_S + R_L)}$$

and

$$V_L = \frac{R_L * V_{in}}{(R_S + R_L)}$$

# The Zener Diode

## The Zener Diode

**In the previous Signal Diode tutorial, we saw that a "reverse biased" diode blocks current in the reverse direction, but will suffer from premature breakdown or damage if the reverse voltage applied across it is too high.**

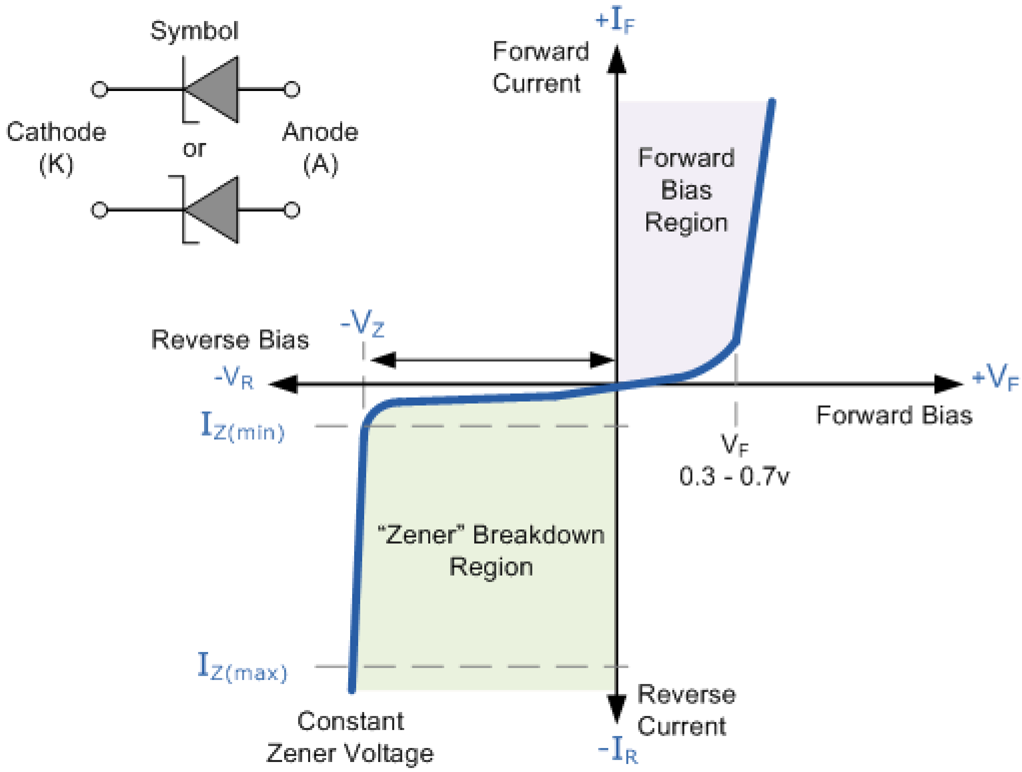
However, the **Zener Diode** or "Breakdown Diode" as they are sometimes called, are basically the same as the standard PN junction diode but are specially designed to have a low pre-determined**Reverse Breakdown Voltage** that takes advantage of this high reverse voltage. The *zener diode* is the simplest types of voltage regulator and the point at which a zener diode breaks down or conducts is called the "Zener Voltage" ( $V_Z$ ).

The **Zener diode** is like a general-purpose signal diode consisting of a silicon PN junction. When biased in the forward direction it behaves just like a normal signal diode passing the rated current, but as soon as a reverse voltage applied across the zener diode exceeds the rated voltage of the device, the diodes breakdown voltage $V_B$ is reached at which point a process called *Avalanche Breakdown* occurs in the semiconductor depletion layer and a current starts to flow through the diode to limit this increase in voltage.

The current now flowing through the zener diode increases dramatically to the maximum circuit value (which is usually limited by a series resistor) and once achieved this reverse saturation current remains fairly constant over a wide range of applied voltages. This breakdown voltage point, $V_B$ is called the "zener voltage" for zener diodes and can range from less than one volt to hundreds of volts.

The point at which the zener voltage triggers the current to flow through the diode can be very accurately controlled (to less than 1% tolerance) in the doping stage of the diodes semiconductor construction giving the diode a specific *zener breakdown voltage*, ( $V_Z$ ) for example, 4.3V or 7.5V. This zener breakdown voltage on the I-V curve is almost a vertical straight line.

### Zener Diode I-V Characteristics




The **Zener Diode** is used in its "reverse bias" or reverse breakdown mode, i.e. the diodes anode connects to the negative supply. From the I-V characteristics curve above, we can see that the zener diode has a region in its reverse bias characteristics of almost a constant negative voltage regardless of the value of the current flowing through the diode and remains nearly constant even with large changes in current as long as the zener diodes current remains between the breakdown current$I_{Z(min)}$ and the maximum current rating $I_{Z(max)}$.

This ability to control itself can be used to great effect to regulate or stabilise a voltage source against supply or load variations. The fact that the voltage across the diode in the breakdown region is almost constant turns out to be an important application of the zener diode as a voltage regulator.

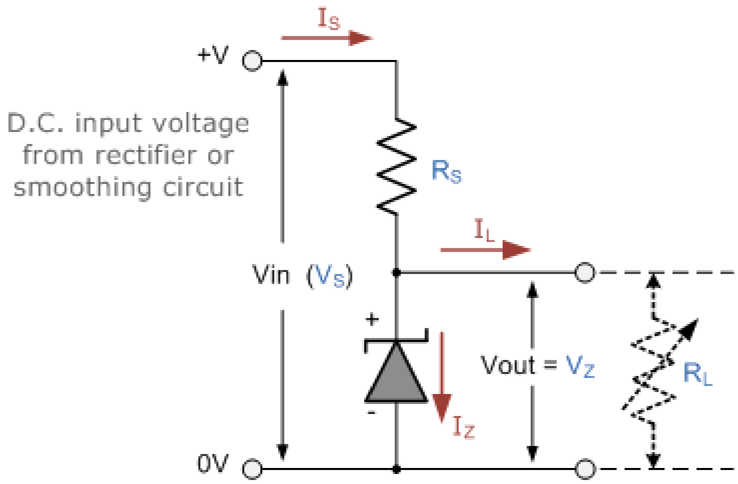
The function of a regulator is to provide a constant output voltage to a load connected in parallel with it in spite of the ripples in the supply voltage or the variation in the load current and the zener diode will continue to regulate the voltage until the diodes current falls below the minimum $I_{Z(min)}$value in the reverse breakdown region.

# The Zener Diode Regulator

**Zener Diodes** can be used to produce a stabilised voltage output with low ripple under varying load current conditions. By passing a small current through the diode from a voltage source, via a suitable current limiting resistor ($R_S$), the zener diode will conduct sufficient current to maintain a voltage drop of Vout.

We remember from the previous tutorials that the DC output voltage from the half or full-wave rectifiers contains ripple superimposed onto the DC voltage and that as the load value changes so to does the average output voltage. By connecting a simple zener stabiliser circuit as shown below across the output of the rectifier, a more stable output voltage can be produced.

## Zener Diode Regulator




The resistor, $R_S$ is connected in series with the zener diode to limit the current flow through the diode with the voltage source, $V_S$ being connected across the combination. The stabilised output voltage $V_{out}$ is taken from across the zener diode. The zener diode is connected with its cathode terminal connected to the positive rail of the DC supply so it is reverse biased and will be operating in its breakdown condition. Resistor $R_S$ is selected so to limit the maximum current flowing in the circuit.

With no load connected to the circuit, the load current will be zero, ( $I_L = 0$ ), and all the circuit current passes through the zener diode which in turn dissipates its maximum power. Also a small value of the series resistor $R_S$ will result in a greater diode current when the load resistance $R_L$ is connected and large as this will increase the power dissipation requirement of the diode so care must be taken when selecting the appropriate value of series resistance so that the zener's maximum power rating is not exceeded under this no-load or high-impedance condition.

The load is connected in parallel with the zener diode, so the voltage across $R_L$ is always the same as the zener voltage, ( $V_R = V_Z$ ). There is a minimum zener current for which the stabilization of the voltage is effective and the zener current must stay above this value operating under load within its breakdown region at all times. The upper limit of current is of course dependant upon the power rating of the device. The supply voltage $V_S$ must be greater than $V_Z$.

One small problem with zener diode stabiliser circuits is that the diode can sometimes generate electrical noise on top of the DC supply as it tries to stabilise the voltage. Normally this is not a problem for most applications but the addition of a large value decoupling capacitor across the zener's output may be required to give additional smoothing.

Then to summarise a little. A zener diode is always operated in its reverse biased condition. A voltage regulator circuit can be designed using a zener diode to maintain a constant DC output voltage across the load in spite of variations in the input voltage or changes in the load current. The zener voltage regulator consists of a current limiting resistor $R_S$ connected in series with the input voltage $V_S$ with the zener diode connected in parallel with the load $R_L$ in this reverse biased condition. The stabilized output voltage is always selected to be the same as the breakdown voltage $V_Z$ of the diode.

## Zener Diode Example No1

A 5.0V stabilised power supply is required to be produced from a 12V DC power supply input source. The maximum power rating $P_Z$ of the zener diode is 2W. Using the zener regulator circuit above calculate:

**a).** The maximum current flowing through the zener diode.

$$\text{Maximum Current} = \frac{\text{Watts}}{\text{Voltage}} = \frac{2w}{5v} = 400mA$$

**b).** The minimum value of the series resistor, $R_S$

$$R_S = \frac{V_S - V_Z}{I_Z} = \frac{12 - 5}{400mA} = 17.5\Omega$$

**c).** The load current $I_L$ if a load resistor of 1kΩ is connected across the zener diode.

$$I_L = \frac{V_Z}{R_L} = \frac{5v}{1000\Omega} = 5mA$$

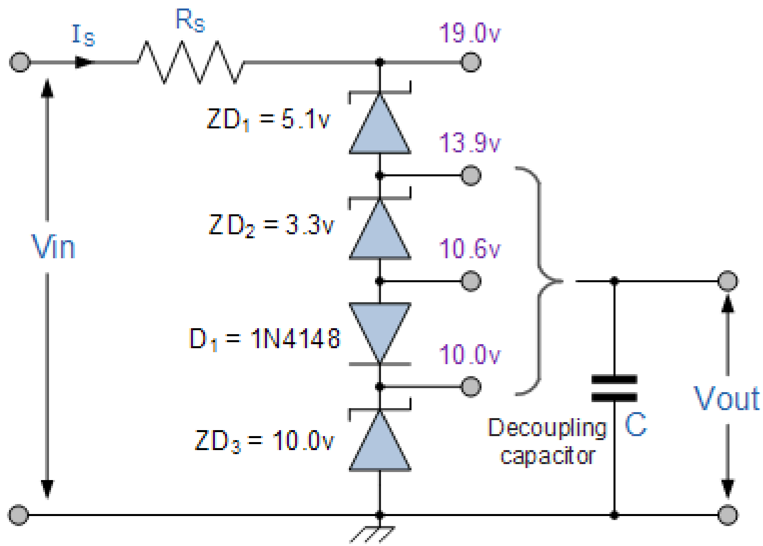
**d).** The zener current $I_Z$ at full load.

$$I_Z = I_S - I_L = 400mA - 5mA = 395mA$$

# Zener Diode Voltages

As well as producing a single stabilised voltage output, zener diodes can also be connected together in series along with normal silicon signal diodes to produce a variety of different reference voltage output values as shown below.

## Zener Diodes Connected in Series




The values of the individual Zener diodes can be chosen to suit the application while the silicon diode will always drop about 0.6 – 0.7V in the forward bias condition. The supply voltage, Vin must of course be higher than the largest output reference voltage and in our example above this is 19v.

A typical **zener diode** for general electronic circuits is the 500mW, *BZX55* series or the larger 1.3W,*BZX85* series were the zener voltage is given as, for example, *C7V5* for a 7.5V diode giving a diode reference number of *BZX55C7V5*.

The 500mW series of zener diodes are available from about 2.4 up to about 100 volts and typically have the same sequence of values as used for the 5% (E24) resistor series with the individual voltage ratings for these small but very useful diodes are given in the table below.

## Zener Diode Standard Zener Voltages

| **BZX55 Zener Diode Power Rating 500mW** | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2.4V | 2.7V | 3.0V | 3.3V | 3.6V | 3.9V | 4.3V | 4.7V |
| 5.1V | 5.6V | 6.2V | 6.8V | 7.5V | 8.2V | 9.1V | 10V |
| 11V | 12V | 13V | 15V | 16V | 18V | 20V | 22V |
| 24V | 27V | 30V | 33V | 36V | 39V | 43V | 47V |
| **BZX85 Zener Diode Power Rating 1.3W** | | | | | | | |
| 3.3V | 3.6V | 3.9V | 4.3V | 4.7V | 5.1V | 5.6 | 6.2V |
| 6.8V | 7.5V | 8.2V | 9.1V | 10V | 11V | 12V | 13V |
| 15V | 16V | 18V | 20V | 22V | 24V | 27V | 30V |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 33V | 36V | 39V | 43V | 47V | 51V | 56V | 62V |

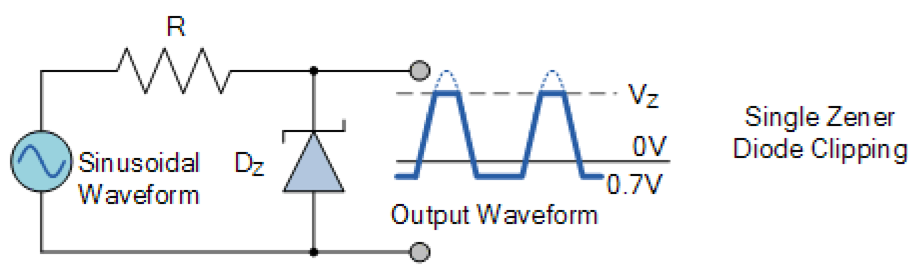
## Zener Diode Clipping Circuits

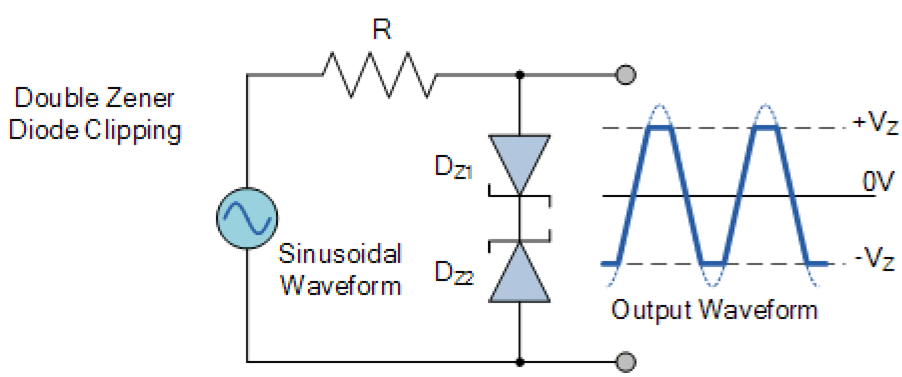
Thus far we have looked at how a zener diode can be used to regulate a constant DC source but what if the input signal was not steady state DC but an alternating AC waveform how would the zener diode react to a constantly changing signal.

Diode clipping and clamping circuits are circuits that are used to shape or modify an input AC waveform (or any sinusoid) producing a differently shape output waveform depending on the circuit arrangement. Diode clipper circuits are also called limiters because they limit or clip-off the positive (or negative) part of an input AC signal. As zener clipper circuits limit or cut-off part of the waveform across them, they are mainly used for circuit protection or in waveform shaping circuits.

For example, if we wanted to clip an output waveform at +7.5V, we would use a 7.5V zener diode. If the output waveform tries to exceed the 7.5V limit, the zener diode will "clip-off" the excess voltage from the input producing a waveform with a flat top still keeping the output constant at +7.5V. Note that in the forward bias condition a zener diode is still a diode and when the AC waveform output goes negative below -0.7V, the zener diode turns "ON" like any normal silicon diode would and clips the output at -0.7V as shown below.

### Square Wave Signal



The back to back connected zener diodes can be used as an AC regulator producing what is jokingly called a "poor man's square wave generator". Using this arrangement we can clip the waveform between a positive value of +8.2V and a negative value of -8.2V for a 7.5V zener diode.

So for example, if we wanted to clip an output waveform between two different minimum and maximum values of say, +8V and -6V, we would simply use two differently rated zener diodes. Note that the output will actually clip the AC waveform between +8.7V and -6.7V due to the addition of the forward biasing diode voltage. In other words a peak-to-peak voltage of 15.4 volts instead of expected 14 volts, as the forward bias volt drop across the diode adds another 0.7 volts in each direction.

This type of clipper configuration is fairly common for protecting an electronic circuit from over voltage. The two zener's are generally placed across the power supply input terminals and during normal operation, one of the zener diodes is "OFF" and the diodes have little or no affect. However, if the input voltage waveform exceeds its limit, then the zener's turn "ON" and clip the input to protect the circuit.

In the next tutorial about diodes, we will look at using the forward biased PN junction of a diode to produce light. We know from the previous tutorials that when charge carriers move across the junction, electrons combine with holes and energy is lost in the form of heat, but also some of this energy is dissipated as photons but we can not see them.

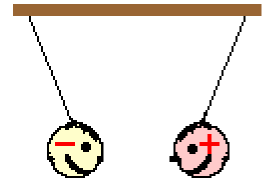
If we place a translucent lens around the junction, visible light will be produced and the diode becomes a light source. This effect produces another type of diode known commonly as the **Light Emitting Diode** which takes advantage of this light producing characteristic to emit light (photons) in a variety of colours and wavelengths.

# ELECTRIC CHARGE'S MOVEMENT

- Electric Field and the Movement of Charge
- Electric Potential
- Electric Potential Difference

Perhaps one of the most useful yet taken-for-granted accomplishments of the recent centuries is the development of electric circuits. The flow of charge through wires allows us to cook our food, light our homes, air-condition our work and living space, entertain us with movies and music and even allows us to drive to work or school safely. In this unit of The Physics Classroom, we will explore the reasons for why charge flows through wires of electric circuits and the variables that affect the rate at which it flows. The means by which moving charge delivers electrical energy to appliances in order to operate them will be discussed in detail.

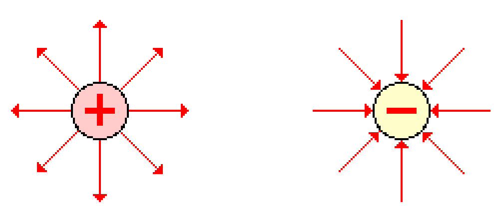
One of the fundamental principles that must be understood in order to grasp electric circuits pertains to the concept of how an electric field can influence charge within a circuit as it movesfrom one location to another. The concept of electric field was first introduced in the unit on Static Electricity. In that unit, electric force was described as a non-contact force. A charged balloon can have an attractive effect upon an oppositely charged balloon even when they are not in contact. The electric force acts over the distance separating the two objects. Electric force is an action-at-a-distance force.



Opposites can attract - even when held some distance apart.

Action-at-a-distance forces are sometimes referred to as field forces. The concept of a **field force** is utilized by scientists to explain this rather unusual force phenomenon that occurs in the absence of physical contact. The space surrounding a charged object is affected by the presence of the charge; an electric field is established in that space. A charged object creates an electric field - an alteration of the space or field in the region that surrounds it. Other charges in that field would feel the unusual alteration of the space. Whether a charged object enters that space or not, the electric field exists. Space is altered by the presence of a charged object; other objects in that space experience the strange and mysterious qualities of the space. As another charged object enters the space and moves *deeper and deeper* into the field, the effect of the field becomes more and more noticeable.

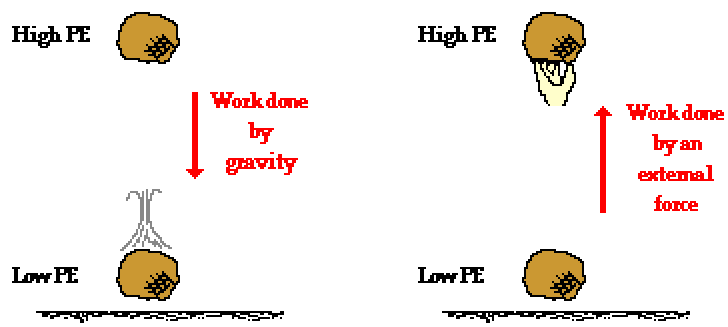
Electric field is a vector quantity whose direction is defined as the direction that a positive test charge would be pushed when placed in the field. Thus, the electric field direction about a positive source charge is always directed away from the positive source. And the electric field direction about a negative source charge is always directed toward the negative source.



The electric field direction is always directed away from positive source charges and towards negative source charges.

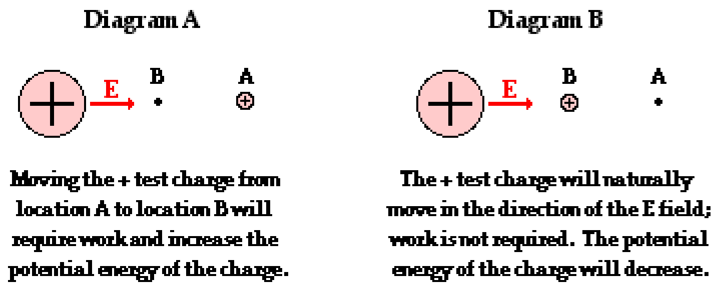
## Electric Field, Work, and Potential Energy

Electric fields are similar to gravitational fields - both involve action-at-a-distance forces. In the case of gravitational fields, the source of the field is a massive object and the action-at-a-distance forces are exerted upon other masses. When the concept of the force of gravity and energy was discussed in Unit 5 of the Physics Classroom, it was mentioned that the force of gravity is an internal or conservative force. When gravity does work upon an object to move it from a high location to a lower location, the object's total amount of mechanical energy is conserved. However, during the course of the falling motion, there was a loss of potential energy (and a gain of kinetic energy). When gravity does work upon an object to move it in the direction of the gravitational field, then the object loses potential energy. The potential energy originally stored within the object as a result of its vertical position is lost as the object moves under the influence of the gravitational field. On the other hand, energy would be required to move a massive object against its gravitational field. A stationary object would not naturally move against the field and gain potential energy. Energy in the form of work would have to be imparted to the object by an external force in order for it to gain this height and the corresponding potential energy.



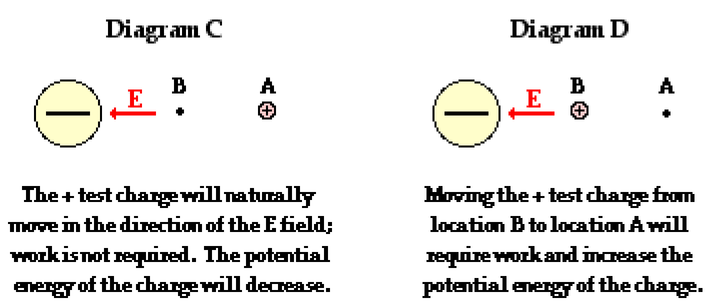

The important point to be made by this gravitational analogy is that work must be done by an external force to move an object against nature - from low potential energy to high potential energy. On the other hand, objects naturally move from high potential energy to low potential energy under the influence of the field force. It is simply natural for objects to move from high energy to low energy; but work is required to move an object from low energy to high energy.

In a similar manner, to move a charge in an electric field against its natural direction of motion would require work. The exertion of work by an external force would in turn add potential energy to the object. The natural direction of motion of an object is from high energy to low energy; but work must be done to move the object *against nature*. On the other hand, work would not be required to move an object from a high potential energy location to a low potential energy location. When this principle is logically extended to the movement of charge within an electric field, the relationship between work, energy and the direction that a charge moves becomes more obvious.




Consider the diagram above in which a positive source charge is creating an electric field and a positive test charge being moved against and with the field. In Diagram A, the positive test charge is being moved against the field from location A to location B. Moving the charge in this direction would be like going against nature. Thus, work would be required to move the object from location A to location B and the positive test charge would be gaining potential energy in the process. This would be analogous to moving a mass in the uphill direction; work would be required to cause such an increase in gravitational potential energy. In Diagram B, the positive test charge is being moved with the field from location B to location A. This motion would be natural and not require work from an external force. The positive test charge would be losing energy in moving from location B to location A. This would be analogous to a mass falling downward; it would occur naturally and be accompanied by a loss of gravitational potential energy. One can conclude from this discussion that the high energy location for a positive test charge is a location nearest the positive source charge; and the low energy location is furthest away.

The above discussion pertained to moving a positive test charge within the electric field created by a positive source charge. Now we will consider the motion of the same positive test charge within the electric field created by a negative source charge. The same principle regarding work and potential energy will be used to identify the locations of high and low energy.




In Diagram C, the positive test charge is moving from location A to location B in the direction of the electric field. This movement would be natural - like a mass falling towards Earth. Work would not be required to cause such a motion and it would be accompanied by a loss of potential energy. In Diagram D, the positive test charge is moving from location B to location A against the electric field. Work would be required to cause this motion; it would be analogous to raising a mass within Earth's gravitational field. Since energy is imparted to the test charge in the form of work, the positive test charge would be gaining potential energy as the result of the motion. One can conclude from this discussion that the low energy location for a positive test charge is a location nearest a negative source charge and the high energy location is a location furthest away from a negative source charge.

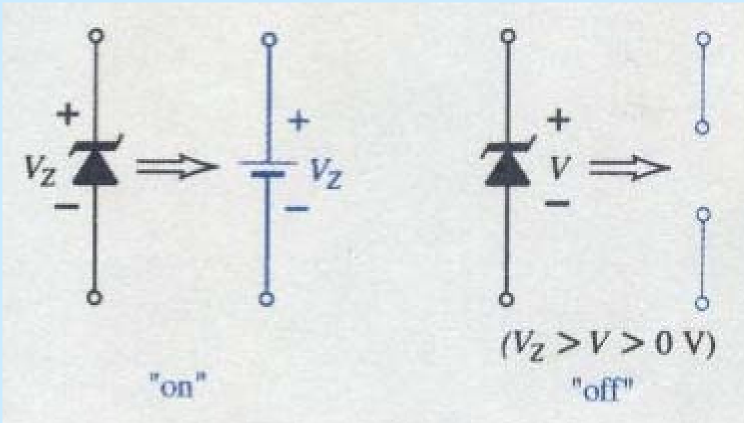
As we begin to discuss circuits, we will apply these principles regarding work and potential energy to the movement of charge about a circuit. Just as we reasoned here, moving a positive test charge against the electric field will require work and result in a gain in potential energy. On the other hand, a positive test charge will naturally move in the direction of the field without the need for work being done on it; this movement will result in the loss of potential energy. Before making this application to electric circuits, we need to first explore the meaning of the concept electric potential.

# Chapter 2

# ZENER DIODE

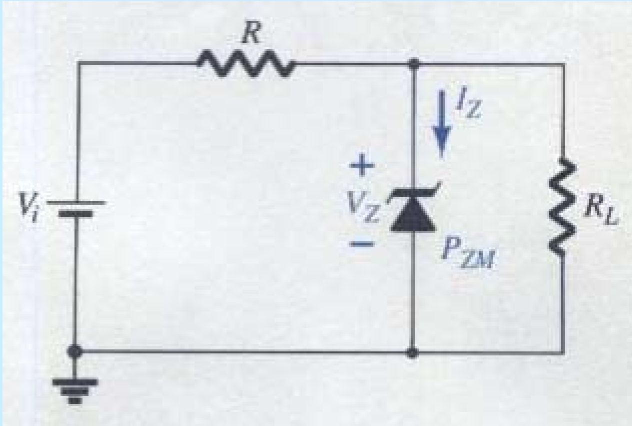
Analysis of networks employing Zener diodes is quite similar to that applied to the analysis of semiconductor diodes in previous sections.

Here, first the state of the diode must be determined followed by a substitution of the appropriate model.
Then, the other unknown quantities of the network will be determined.




Equivalent circuit

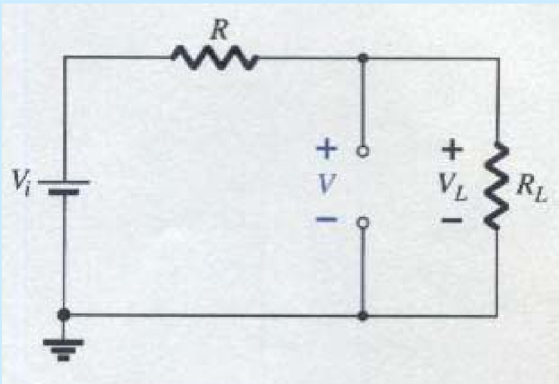
(i) $V_i$ and $R$ Fixed




Basic zener regulator

Analysis procedure

Step (1) Determine the state of the zener diode by removing it from the network and calculating the voltage across the resulting open circuit.



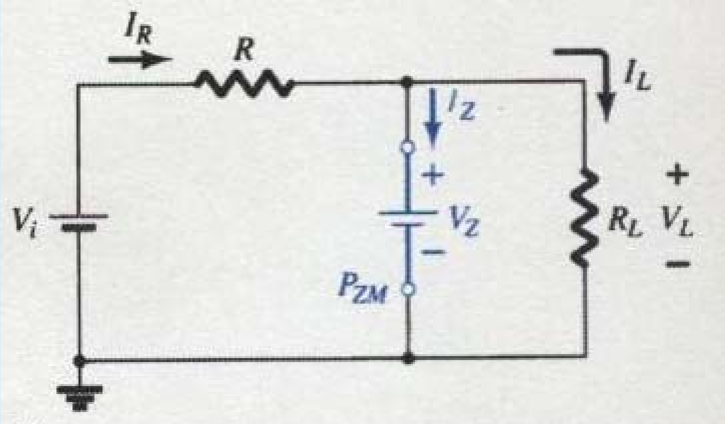

$$V = V_L = \frac{R_L V_i}{R + R_L}$$

If $V \geq V_Z$, the Zener diode is "on"

If $V < V_Z$, the diode is "off"

Step (2) Substitute the appropriate equivalent circuit and solve for the desired unknowns.

Ex: In case of “on” state.




Voltages across the parallel elements must be the same.

$$V_L = V_Z$$

$$I_R = I_Z + I_L$$

$$I_Z = I_R - I_L$$

$$P_Z = V_Z I_Z$$

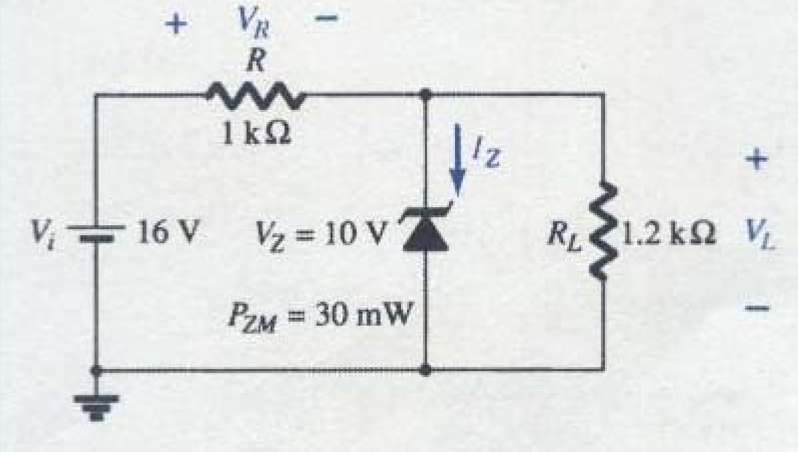
$$I_L = \frac{V_L}{R_L}$$

$$I_R = \frac{V_R}{R} = \frac{V_i - V_L}{R}$$

When the system is turned on, the Zener diode will turn “on” as soon as the voltage across The Zener diode is $V_z$ volts. It will then “lock in” at this level and never reach the higher Level of *V* volts.

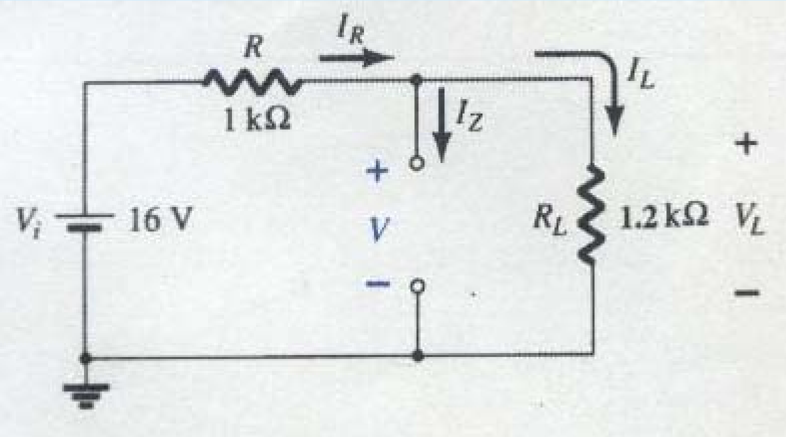
Zener diodes are most frequently used in *regulator* networks or as a reference voltage. Regulator is designed to maintain a fixed voltage across the load $R_L$. For values of applied voltage greater than required to turn the Zener diode “on”, the voltage across the load will be maintained at $V_z$ volts.

Example (1): (a) determine $V_L$, $V_R$, $I_z$ and $P_z$.
(b) change $R_L$ to 3 kOhm.

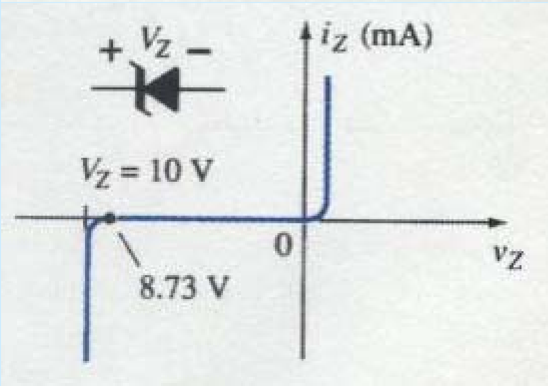



Solution (a)

Step (1) Removing the diode




$$V = \frac{R_L V_i}{R + R_L} = \frac{1.2\ \text{k}\Omega(16\ \text{V})}{1\ \text{k}\Omega + 1.2\ \text{k}\Omega} = 8.73\ \text{V}$$




V < Vz
The diode is "off"

Step (2) Substitute open-circuit equivalent.

$$V_L = V = \mathbf{8.73\ V}$$

$$V_R = V_i - V_L = 16\ \text{V} - 8.73\ \text{V} = \mathbf{7.27\ V}$$

$$I_Z = \mathbf{0\ A}$$

$$P_Z = V_Z I_Z = V_Z(0\ \text{A}) = \mathbf{0\ W}$$

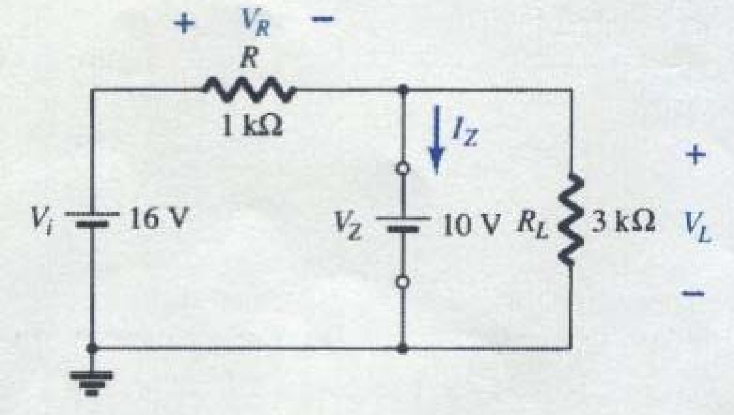
Solution (b)

Step (1) Removing the diode

$$V = \frac{R_L V_i}{R + R_L} = \frac{3\ \text{k}\Omega(16\ \text{V})}{1\ \text{k}\Omega + 3\ \text{k}\Omega} = 12\ \text{V}$$

V > Vz , the diode is “on”

Step (2) Substitute the equivalent circuit.




$$V_L = V_Z = \mathbf{10\ V}$$

$$V_R = V_i - V_L = 16\ \text{V} - 10\ \text{V} = \mathbf{6\ V}$$

$$I_L = \frac{V_L}{R_L} = \frac{10\ \text{V}}{3\ \text{k}\Omega} = 3.33\ \text{mA}$$

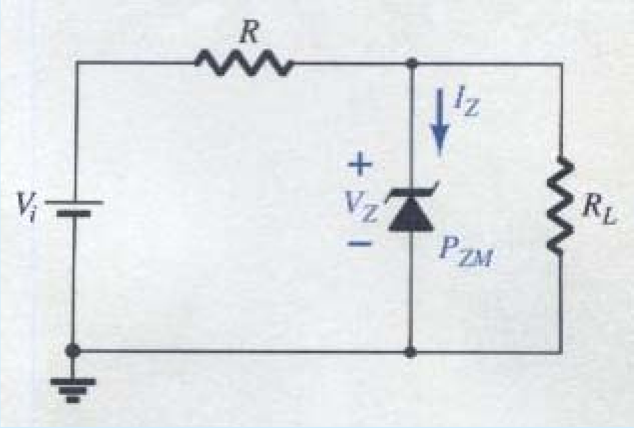
$$I_R = \frac{V_R}{R} = \frac{6\ \text{V}}{1\ \text{k}\Omega} = 6\ \text{mA}$$

$$I_Z = I_R - I_L\ [\text{Eq. (2.18)}]$$
$$= 6\ \text{mA} - 3.33\ \text{mA}$$
$$= \mathbf{2.67\ mA}$$

$$P_Z = V_Z I_Z = (10\ \text{V})(2.67\ \text{mA}) = \mathbf{26.7\ mW}$$

(ii) Fixed $V_i$, Variable $R_L$

Too small a load resistance $R_L$ will result in a voltage $V_L$ across the load resistor less than $V_z$ and the Zener device will be in the "off" state.
To determine the minimum load resistance that will turn the Zener diode on, simply calculate the value of $R_L$ that will result in a load voltage $V_L = V_z$.




$$V_L = V_Z = \frac{R_L V_i}{R_L + R}$$

$$R_{L_{min}} = \frac{R V_Z}{V_i - V_Z}$$

Any load resistance value greater than the RL obtained above will ensure that the Zener diode is in the "on" state and the diode can be replaced by its $V_z$ source equivalent.

Then, we obtain

$$I_{L_{max}} = \frac{V_L}{R_L} = \frac{V_Z}{R_{L_{min}}}$$

Once the diode is in the "on" state, the voltage across R remains fixed at

$$V_R = V_i - V_Z$$

$$I_R = \frac{V_R}{R}$$

The Zener current

$$I_Z = I_R - I_L$$

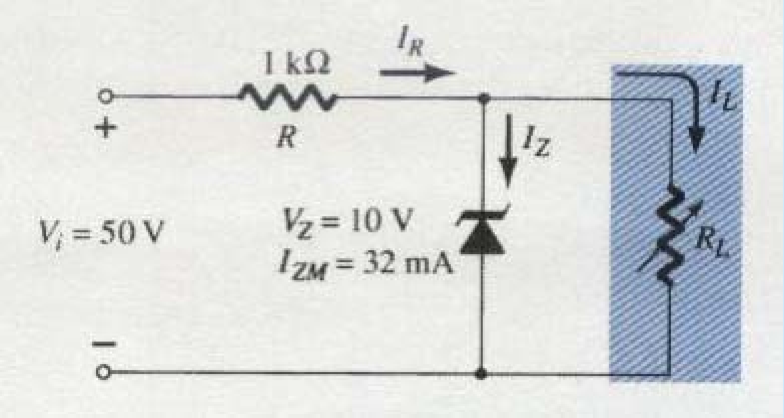
Resulting in a minimum $I_z$ when $I_L$ is a maximum and a maximum $I_z$ when $I_L$ is a minimum value since $I_R$ is constant.

$$I_{L_{min}} = I_R - I_{ZM}$$

$$R_{L_{max}} = \frac{V_Z}{I_{L_{min}}}$$

Example (2) (a) Determine the range of $R_L$ and $I_L$ that will result in $V_{RL}$ being maintained at 10V.

(b) Determine the maximum wattage rating of the diode.




Solution (a):

First, determine the value of $R_L$ that will turn the Zener diode on.

$$R_{L_{min}} = \frac{RV_Z}{V_i - V_Z} = \frac{(1\ \text{k}\Omega)(10\ \text{V})}{50\ \text{V} - 10\ \text{V}} = \frac{10\ \text{k}\Omega}{40} = \mathbf{250\ \Omega}$$

$$V_R = V_i - V_Z = 50\ \text{V} - 10\ \text{V} = \mathbf{40\ V}$$

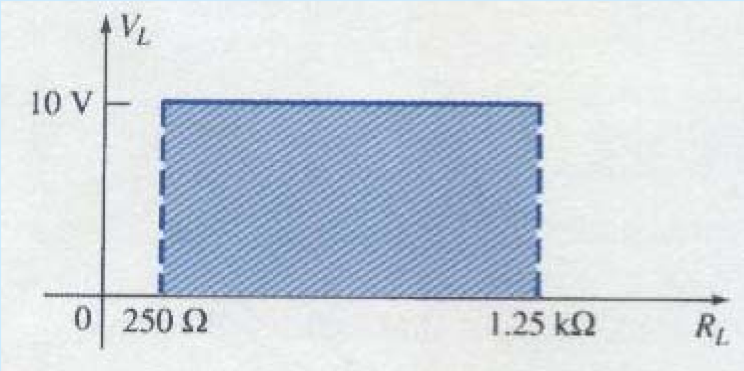
$$I_R = \frac{V_R}{R} = \frac{40\ \text{V}}{1\ \text{k}\Omega} = \mathbf{40\ mA}$$

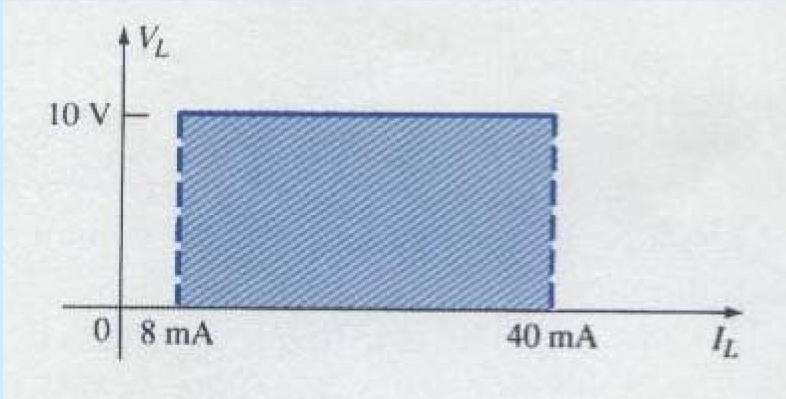
$$I_{L_{min}} = I_R - I_{ZM} = 40\ \text{mA} - 32\ \text{mA} = \mathbf{8\ mA}$$

the maximum value of $R_L$:

$$R_{L_{max}} = \frac{V_Z}{I_{L_{min}}} = \frac{10\ \text{V}}{8\ \text{mA}} = \mathbf{1.25\ k\Omega}$$

The range of $R_L$ and $I_L$ that will result in $V_{RL}$ being maintained at 10V.



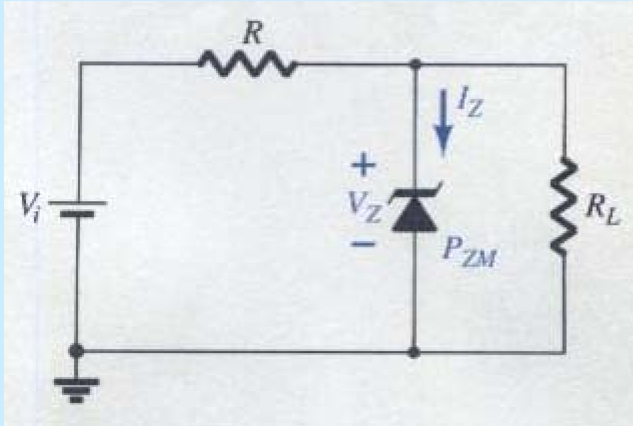




Solution (b):

$$P_{max} = V_Z I_{ZM}$$
$$= (10\text{ V})(32\text{ mA}) = \mathbf{320\text{ mW}}$$

(iii) Fixed $R_L$, Variable $V_i$

For fixed value of $R_L$, the voltage $V_i$ must be sufficiently large to turn the Zener diode on. The minimum turn-on voltage $V_i = V_{imin}$ is determined by




$$V_L = V_Z = \frac{R_L V_i}{R_L + R}$$

$$\boxed{V_{i_{min}} = \frac{(R_L + R)V_Z}{R_L}}$$

The maximum value of $V_i$ is limited by the maximum Zener current $I_{ZM}$. Since $I_{ZM} = I_R – I_L$,

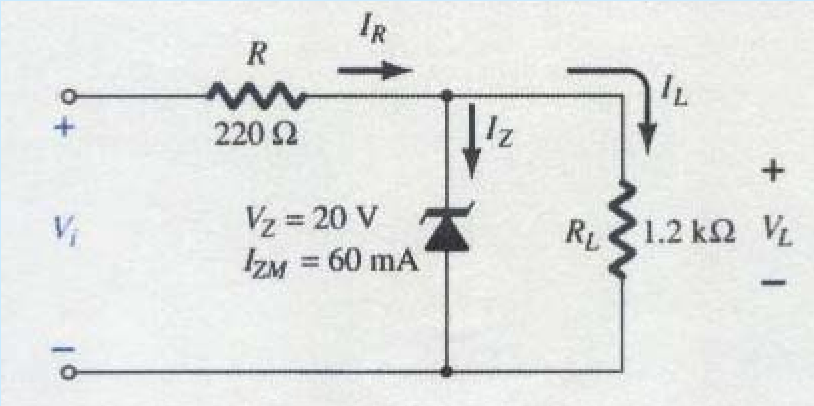
$$\boxed{I_{R_{max}} = I_{ZM} + I_L}$$

Since $I_L$ is fixed at $V_z/ R_L$ and $I_{ZM}$ is the maximum value of $I_z$, the maximum $V_i$ is defined by

$$V_{i_{max}} = V_{R_{max}} + V_Z$$

$$\boxed{V_{i_{max}} = I_{R_{max}} R + V_Z}$$

Example (3): Determine the range of values of $V_i$ that will maintain the Zener diode in the "on" state.



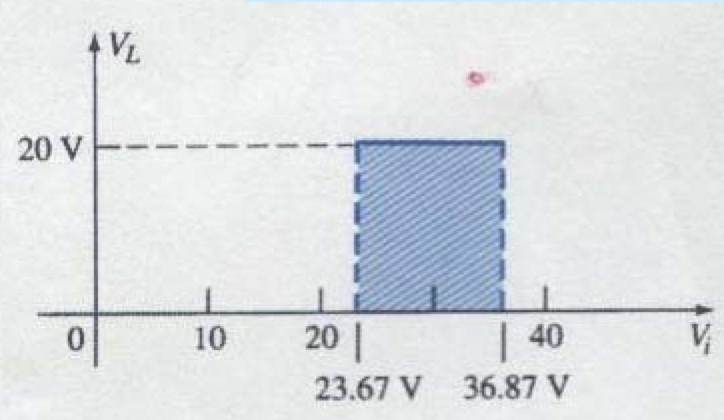

Solution:

$$V_{i_{min}} = \frac{(R_L + R)V_Z}{R_L} = \frac{(1200\ \Omega + 220\ \Omega)(20\ \text{V})}{1200\ \Omega} = \mathbf{23.67\ V}$$

$$I_L = \frac{V_L}{R_L} = \frac{V_Z}{R_L} = \frac{20\ \text{V}}{1.2\ \text{k}\Omega} = 16.67\ \text{mA}$$

$$I_{R_{max}} = I_{ZM} + I_L = 60\ \text{mA} + 16.67\ \text{mA}$$
$$= 76.67\ \text{mA}$$

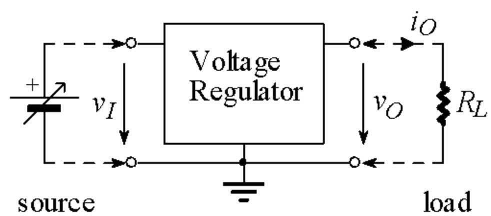
$$V_{i_{max}} = I_{R_{max}}R + V_Z$$
$$= (76.67\ \text{mA})(0.22\ \text{k}\Omega) + 20\ \text{V}$$
$$= 16.87\ \text{V} + 20\ \text{V}$$
$$= \mathbf{36.87\ V}$$



# Voltage Regulators

The purpose of a voltage regulator is to provide a constant dc output that is practically independent on the variations of: the input voltage, output load current and temperature.

In Romanian the circuit is called “Stabilizator de tensiune”




The two fundamental classes of voltage regulators are:
- linear regulators and
- switching regulators.

## *Voltage Regulators Parameters*

The two basic aspects of voltage regulation are: line regulation and load regulation.

**Line regulation** can be defined as the percentage change in the output voltage for one volt change in the input (line) voltage (measured in %/V): $LineRg = \frac{\Delta v_O}{V_O} \cdot \frac{100}{\Delta v_I}$.

**Load regulation** can be defined as the percentage change in output voltage for a given change in current (e.g. from no-load “$NL$” to full-load “$FL$”): $LoadRg = \frac{V_{NL} - V_{FL}}{V_{FL}} \cdot 100$.

**For small variations** of the output voltage the differentials can be used and:

$$dv_O = \frac{dv_I}{S} - R_o \cdot di_O + TC \cdot dT .$$

From this equation, the parameters of the voltage regulator can be found:

$S = \left.\frac{dv_I}{dv_O}\right|_{di_O, dT=0}$ - The $S$ factor, regulation coefficient (Romanian: coeficient de stabilizare);

$R_o = -\left.\frac{dv_O}{di_O}\right|_{dv_I, dT=0}$ - The output resistance (or internal resistance of the source);

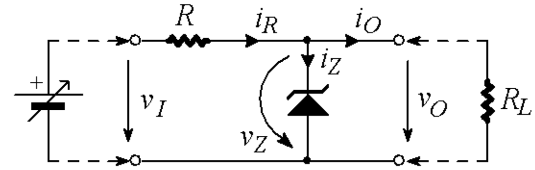
$TC = \left.\frac{dv_O}{dT}\right|_{dv_I, dv_O=0}$ - The thermal coefficient, (Romanian: $S_T$, coeficient de temperatură).

The small variation parameters of the regulator can be computed using the small signal equivalent circuit.

## *Linear Regulators*

There are two basic types of linear regulators: series regulator and shunt regulator.

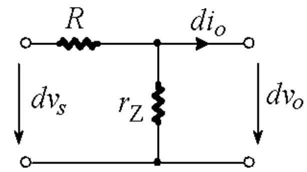
### The Zener Diode Voltage Regulator




This is the simpler shunt regulator; it consists on a Zener diode in parallel with the load and a series resistor (between input and output).

Input voltage variations and output current variations are converted by the circuit in Zener current variations. As long as: $I_{Z\min} < i_Z < I_{Z\max}$, the Zener voltage is almost constant: $v_Z = \text{ct} = V_Z$ and $v_O = v_Z = \text{ct}$.

The small variation parameters of the voltage the regulator are computed based on the small signal equivalent circuit, where the Zener diode is replaced by its dynamic resistance:




$$S = \left.\frac{dv_I}{dv_O}\right|_{di_O=0} = \frac{R + r_Z}{r_Z} \cong \frac{R}{r_Z}$$ (the voltage divider rule);

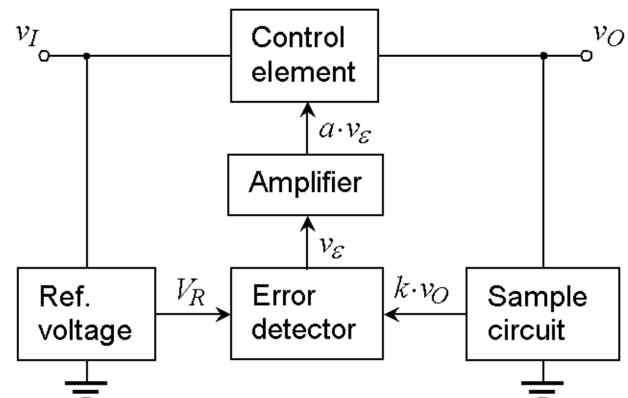
$$R_o = -\left.\frac{dv_O}{di_O}\right|_{dv_I=0} = r_Z \parallel R \cong r_Z$$; the approximations are correct for the usual case: $r_Z \ll R$.

The output resistance of the voltage regulator depends directly on the dynamic resistance of the Zener diode (de aceea în română circuitul se numeşte “Stabilizator parametric”).

### The Series Voltage Regulator

The control element is in series with the load; between input and output. The sample circuit senses a change in the output voltage. The error detector compares the sampled voltage with a reference voltage and causes the control element to compensate in order to maintain a constant output voltage:

$v_\varepsilon = V_R - k \cdot v_O = 0$ and $v_O = V_R / k = \text{ct}$.

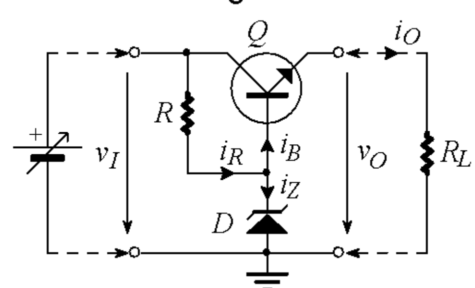



### The Emitter-Follower Series Regulator

The simplest series regulator consists on an emitter-follower and a Zener diode regulator (that provides the reference voltage). The circuit is presented in the next figure.

The output voltage is constant: $v_O = V_Z - V_{BE} = \text{ct}$.

The emitter follower reduces the output current variation by a factor of $\beta$: $\Delta i_Z = \dfrac{-\Delta i_O}{\beta}$.



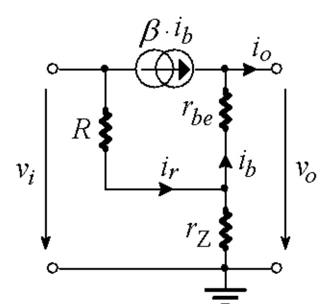

The load current pass through the series transistor, the voltage across the series transistor is: $v_{CE} = v_I - v_O$ and the power dissipation is: $P_D = v_{CE} \cdot i_E = (v_I - v_O) \cdot i_O$.

*Q* is a power transistor and it is often used with a heatsink.

The regulator parameters can be found from the small-signal equivalent circuit:

$$S = \left.\frac{dv_I}{dv_O}\right|_{di_O=0} = \left.\frac{v_i}{v_o}\right|_{i_o=0} = \frac{R + r_Z}{r_Z} \cong \frac{R}{r_Z};$$

$$R_o = -\left.\frac{dv_O}{di_O}\right|_{dv_I=0} = -\left.\frac{v_o}{i_o}\right|_{v_i=0} = \frac{(r_{be} + R \parallel r_Z) \cdot i_b}{(\beta + 1) \cdot i_b} \cong \frac{r_{be} + r_Z}{\beta + 1} = \frac{1}{g_m} + \frac{r_Z}{\beta}.$$

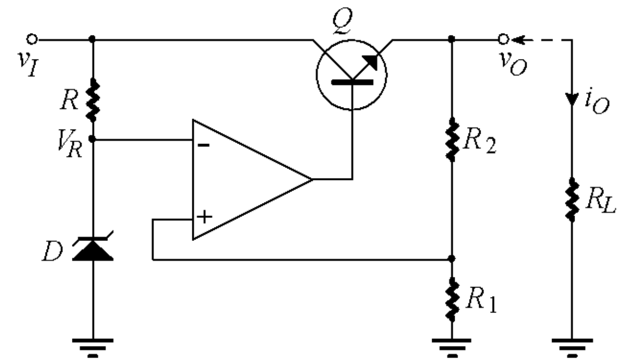



The $S$ factor can be much greater than that of the zener regulator, because $R$ can be much greater, beeing passed by the Zener current, that is much lower than the output current.

The output resistance is much smaller than for the zener regulator, the dynamic resistance of the zener beeing reduced by the high $\beta$ factor (and $1/g_m = r_e$ has a very low value).

### The Basic Op Amp Series Regulator

The reference voltage $V_R$ is the input of the noninverting amplifier and the $R_1/R_2$ voltage divider forms the negative feedback network. The ideal closed loop gain is:

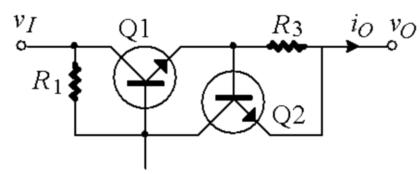



$$A = 1 + \frac{R_2}{R_1}.$$

Therefore the regulated voltage is a constant value determined by the Zener voltage and the resistor ratio: $v_O = \left(1 + \frac{R_2}{R_1}\right) \cdot V_R$.

### The Short-Circuit or Overload Protection

If an excessive amount of load (output) current is drawn, the series-pass transistor $Q_1$ can be quickly destroyed. One method of current limiting to prevent overloads is the "constant current limiting"; it consists of transistor $Q_2$ and resistor $R_3$ of the circuit in the next figure.



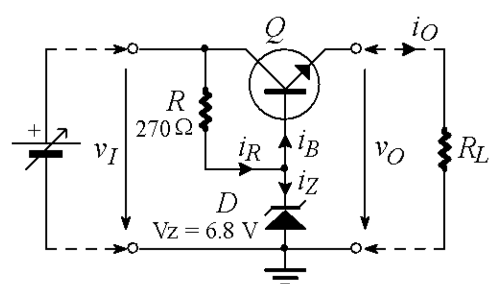

The voltage load through $R_3$ creates a voltage from base to emitter of $Q_2$. For normal load current the voltage drop across $R_3$ is small and $Q_2$ is off. When $i_O$ reaches the limiting value, the voltage drop across $R_3$ is sufficient to turn on $Q_2$. Enough $Q_1$ base current is diverted into $Q_2$ so that $i_O$ is limited to its maximum value:

$$I_{O\max} \cong \frac{V_D}{R_3} = \frac{0.7}{R_3}.$$

Since $v_{BE}$ voltage is limited to about 0.7 V for a silicon transistor, the voltage drop across $R_3$ is held to this value and the load current is limited to $I_{O\max}$.

### Application

**VR – P1**.




1. In the next figure consider $V_I = 10$ V and $V_{BE} = 0.7$ V. What is $v_O$?
2. If $\beta = 50$ and $R_L = 22\ \Omega$ what is the base current and the zener current for $V_I = 10$ V?
3. If $v_I$ varies from 10 to 15 V and $R_L$ varies from 22 Ω to 500 Ω what is the maximum power dissipation in the transistor, in the Zener and in $R$?
4. $R_L$ changes from 22 Ω to 500 Ω. If $\beta = 50$ and $r_Z = 5\ \Omega$, what is the approximate change in output voltage and the load regulation (expressed in %)?

1. $V_O = V_Z - V_{BE} = 6.8 - 0.7 = 6.1\,\mathrm{V}$.

2. $i_R = i_Z + i_B$. $i_Z = i_R - i_B = \frac{v_I - V_Z}{R} - \frac{i_O}{\beta} = 11.9m - 5.5m = 6.4\,\mathrm{mA}$;

$$i_O = \frac{10-6{,}1}{270} = 11.9\,\mathrm{mA},\ i_O = \frac{V_O}{R_L} = \frac{6.1}{22} = 0.277\,\mathrm{A} = 277\mathrm{mA},\ i_B = \frac{i_O}{\beta} = \frac{277m}{50} = 5.5\,\mathrm{mA}.$$

3. The transistor power dissipation is: $P_{dQ} = v_{CE} \cdot i_E = (v_I - V_O) \cdot i_O$;

Its maximum power dissipation is: $P_{dQM} = (v_{IM} - V_O) \cdot i_{OM} = (15 - 6.1) \cdot 0.277 = 2.47\,\mathrm{W}$.

The zener diode power dissipation is: $P_{dZ} = V_Z \cdot i_Z \cong V_Z \cdot \left(\frac{v_I - V_Z}{R} - \frac{i_O}{\beta}\right)$; its maximum is:

$$P_{dZM} = V_Z \cdot \left(\frac{v_{IM} - V_Z}{R} - \frac{V_O}{\beta \cdot R_{LM}}\right) = 6.8 \cdot \left(\frac{15-6.8}{270} - \frac{6.1}{50 \cdot 500}\right) = 0.207\,\mathrm{W}.$$

The resistance power dissipation is: $P_{dR} = \frac{(v_I - V_Z)^2}{R}$;

Its maximum power dissipation is: $P_{dRM} = \frac{(v_{IM} - V_Z)^2}{R} = \frac{(15-6.8)^2}{270} = 0.25\,\mathrm{W}$.

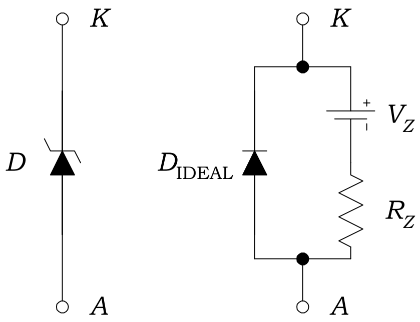
4. With $V_{BE} = \mathrm{ct}$, the output voltage $v_O$ is modified because of $v_Z$ variation (produced by $i_Z$ variation). To simplify the computing we will consider a constant $v_Z\ (= V_Z)$ when computing the zener current variation, $\Delta i_Z$. The limits of the zener current are given by the limits of the output current (load resistance limits); the minimum zener current has been computed for the maximum load current (minimum load resistance) at point 2. The maximum zener current results for the minimum load current (maximum load resistance):

$$i_{Z\max} = \frac{v_I - V_Z}{R} - \frac{i_{O\min}}{\beta} = i_R - \frac{V_O}{\beta \cdot R_{L\max}} = 11.9m - \frac{6.1}{50 \cdot 500} = 11.9m - 502m = 11.7\ \mathrm{mA},$$

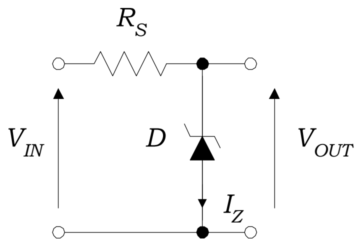
$$\Delta v_Z = r_Z \cdot \Delta i_Z = 5 \cdot (11.7 - 6.4)m = 26.5\,\mathrm{mV}.\ LoadRg = \frac{\Delta v_O}{V_O}100 = \frac{26.5m}{6.1}100 = 0.43\,\%.$$

# Problem Set
## Zener Diodes

The model of a Zener diode is shown below. When forward biased (*A* more positive than *K*) the Zener acts like an ideal diode $D_{\text{IDEAL}}$. When reverse biased (*K* more positive than *A*) the Zener is modelled as an ideal voltage source $V_Z$ in series with the resistance $R_Z$.



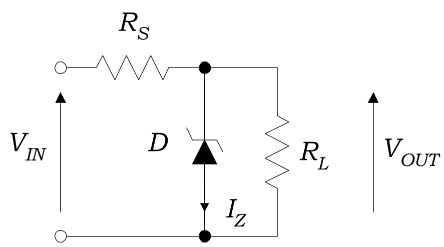

**Question 1**
For the circuit shown below calculate the Zener diode current $I_Z$ and the circuit output voltage $V_{OUT}$ assuming (a) $R_Z = 0$ and (b) $R_Z = 20\,\Omega$.




$V_{IN} = 12\,\text{V}$
$R_S = 320\,\Omega$
$I_{Z(MIN)} = 5\,\text{mA}$
$V_Z = 8.2\,\text{V}$

**Question 2**
The circuit in Question 1 is connected to an unregulated voltage source $V_S$ that varies between 10.0 V and 20.0 V. Calculate the corresponding variation in output voltage assuming (a) $R_Z = 0\,\Omega$ and (b) $R_Z = 20\,\Omega$.

**Question 3**
The circuit below shows a simple Zener regulator with a permanently connected load $R_L$. Calculate the Zener diode current $I_Z$ and the circuit output voltage $V_{OUT}$ assuming (a) $R_Z = 0$ and (b) $R_Z = 20\,\Omega$.




$V_{IN} = 12\,\text{V}$
$R_S = 75\,\Omega$
$I_{Z(MIN)} = 5\,\text{mA}$
$V_Z = 8.2\,\text{V}$
$R_L = 250\,\Omega$

**Question 4**

Design a Zener regulator to supply 8.2 V to a constant, permanently connected, $50\,\Omega$ load. The input to the circuit is an unregulated DC supply in the range 15.0 V to 24.0 V. Assume that the Zener diode needs 5 mA to ensure operation and $R_Z = 0\,\Omega$.

**Notes:**

1. The Zener diode must have 5 mA flowing through it at ALL times for the circuit to function correctly.
2. You need to calculate the value and power rating of the source resistor together with the power rating of the Zener diode.)

**Question 5**

With reference to your design in Question 4, calculate the power dissipated in the Zener diode if the load is accidentally disconnected. Is this a problem?

# Outline Solutions

### Question 1

(b) Sum the voltages around the loop to get $V_{IN} = I_Z R_S + \underbrace{I_Z R_Z + V_Z}_{V_{OUT}}$.

Thus $I_Z = \dfrac{V_{IN} - V_Z}{R_S + R_Z} = \underline{11.176\,\text{mA}}$ and $V_{OUT} = I_Z R_Z + V_Z = \underline{8.424\,\text{V}}$.

### Question 2

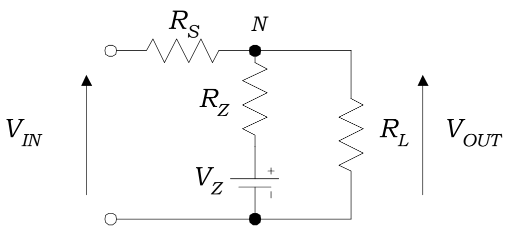
(b) $V_{S(MIN)} = 10.0\,\text{V}$ and $V_{S(MAX)} = 20.0\,\text{V}$. Using the results of Question 1 we get

$I_{Z(MIN)} = \dfrac{V_{S(MIN)} - V_Z}{R_S + R_Z} = \underline{5.294\,\text{mA}}$ giving $V_{OUT(MIN)} = I_{Z(MIN)} R_Z + V_Z = \underline{8.306\,\text{V}}$. Similarly,

$V_{OUT(MAX)} = \underline{8.894\,\text{V}}$. The variation in the output is $8.894 - 8.306\,\text{V}$ or $\underline{0.588\,\text{V}}$ or $\underline{7.1\%}$ Note that the input variation is $\underline{10.0\,\text{V}}$ or $\underline{100.0\,\%}$.

### Question 3

(b) Replace the Zener diode with its equivalent circuit:




Sum the currents leaving the node $N$ to get $\dfrac{V_{OUT} - V_{IN}}{R_S} + \dfrac{V_{OUT} - V_Z}{R_Z} + \dfrac{V_{OUT}}{R_L} = 0$. Now solve for the

output voltage $V_{OUT} = \dfrac{\frac{V_{IN}}{R_S} + \frac{V_Z}{R_Z}}{\frac{1}{R_S} + \frac{1}{R_Z} + \frac{1}{R_L}} = \underline{8.465\,\text{V}}$. The Zener current is $I_Z = \dfrac{V_{OUT} - V_Z}{R_Z} = \underline{13.267\,\text{mA}}$.

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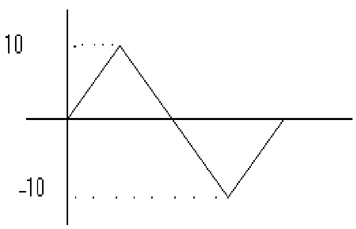
Electronics 1
Problem set (3)
Zener Diode

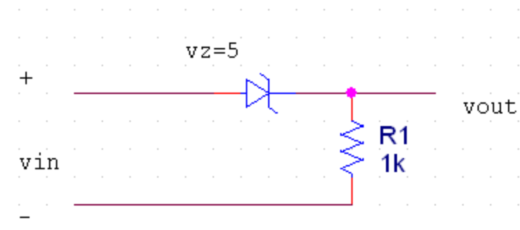
## Problem#1:

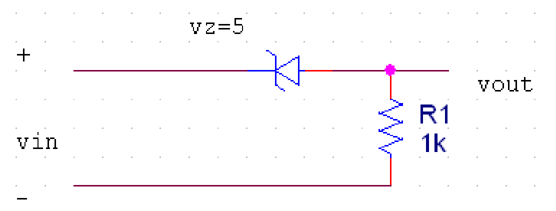
For each circuit below, assume voltage drop (0.7)

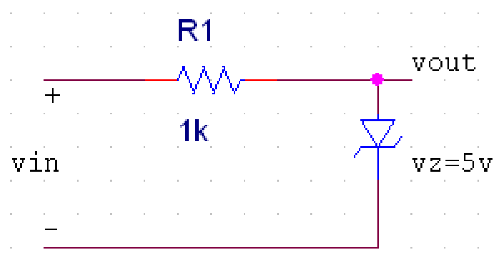
a-Sketch the output voltage waveform.

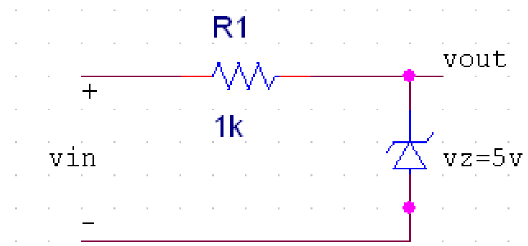
b-Sketch transfer curve



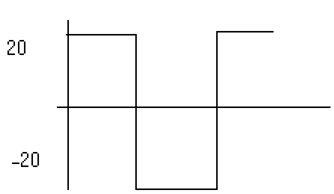



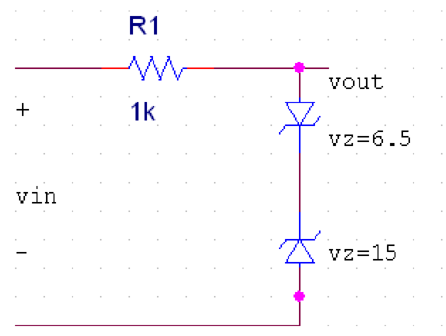

## Problem#2:

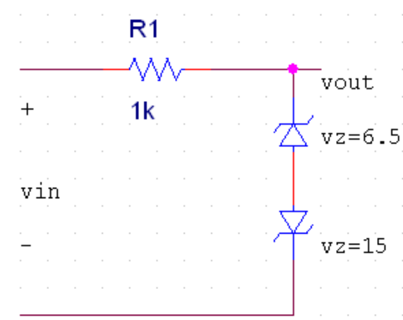
For each circuit below, assume voltage drop (0.7)

a-Sketch the output voltage waveform.

b-Sketch transfer curve



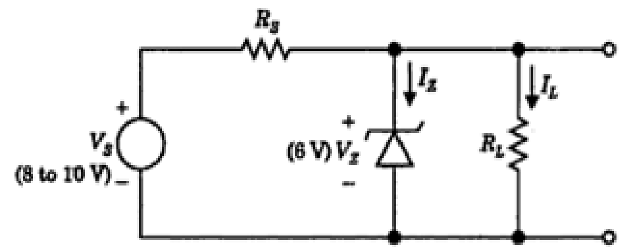



## Problem #3

The regulated in figure is provide 6v load voltage for all load current s, I load ≤.5A.The unregulated supply varies between 8 and10 V,and the zener diode provides regulation for $Iz > 0$, determine

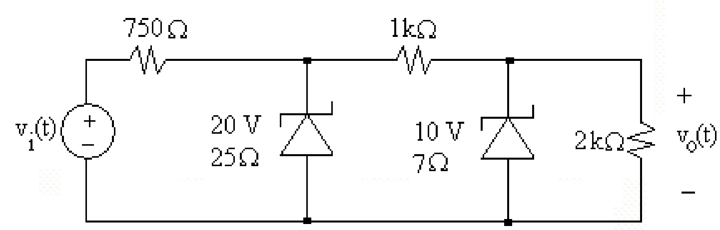
a-the series resistance Rs needed

b-the power dissipation rating of the zener diode




## Problem #4

Figure shows a regulator circuit with two zener diodes. The first stage is called a preregulator. The source has a large ripple and varies from 35 V to 60 V. Determine the final output voltage




## Problem #5

In the regulator circuit, the resistance R is arbitrarily chosen as 20 Ω while the load resistance is 100Ω. The ideal zener has a zener voltage of 15 V. The input voltage $v_S(t)$ varies as 15 + 9 sin (1000t) V. Sketch the output voltage