Course: Basic Electronics (EC21101)

Course Instructor: Prof. Kapil Debnath

Lecture 4: diode circuits

- **Contact Email: k.debnath@ece.iitkgp.ac.in**
- **website: https://kdebnath8.wixsite.com/nanophotonics**

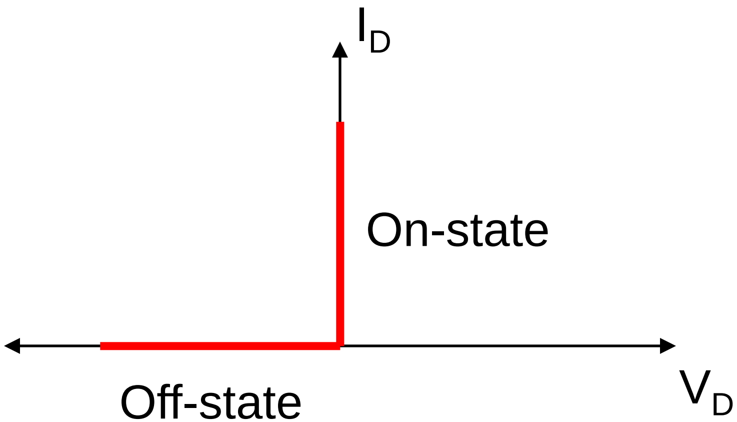
- **Office: R314, ECE Dept, Discussion time: Friday 5pm**

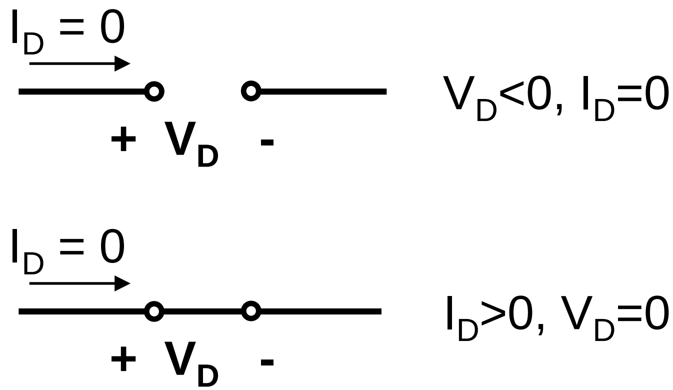
Diode models for DC analysis

Before we go into various diode circuits, it will be helpful to first familiarize ourselves with various diode models used for circuit analysis. Diode models refer to the mathematical models used to approximate the actual behavior of real diodes to enable calculations and circuit analysis. As we have seen in the previous lecture a diode's I-V curve is nonlinear. This nonlinearity complicates calculations in circuits involving diodes so simpler models are often required. Depending on the accuracy needed for a particular circuit analysis, we use various mathematical models of diodes:

1. Idealized diode:

This is the simplest diode model, where the diode is considered to be a short circuit under forward bias and considered open circuit for reverse bias. The IV characteristic of an ideal diode is shown below.





Notice, here the cutin voltage and also the forward resistance are considered as zero

Diode models for DC analysis

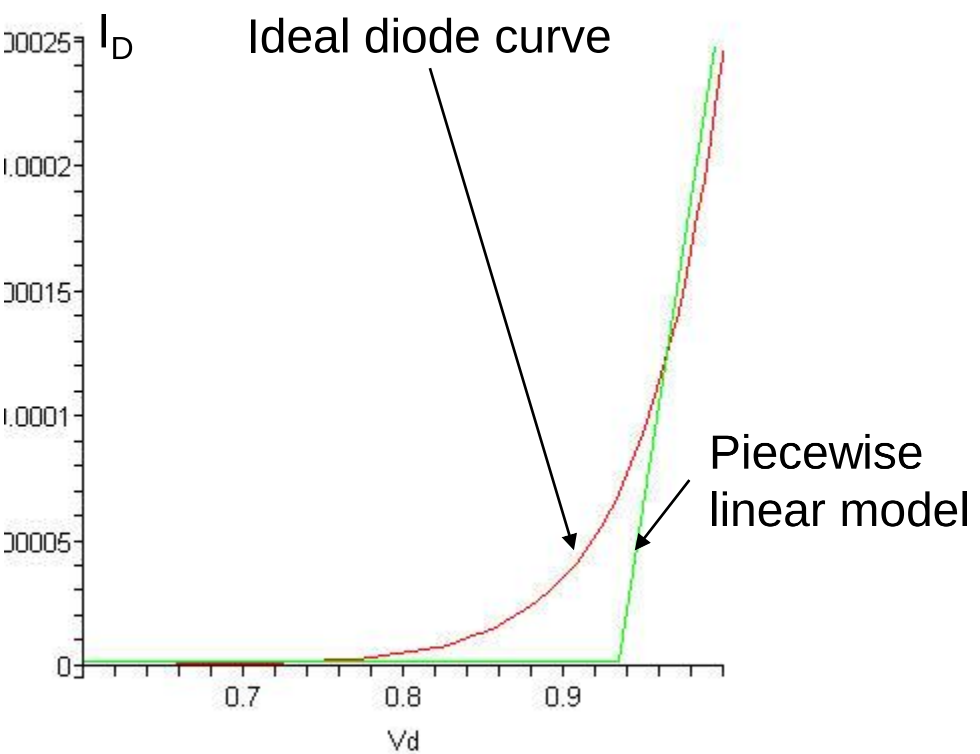
2. Piecewise linear model:

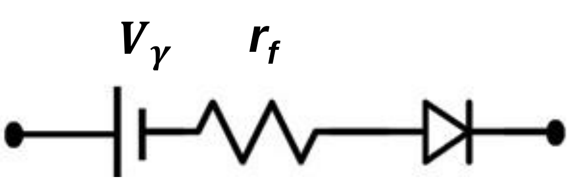
Idealized diode model discussed in the last slide is the simplest diode model, however, it is also the least accurate model. Another simpler mathematical model to approximate diode IV characteristics is piecewise linear model, where the IV curve is split into several segments and approximated by straight lines.

For $V_D \geq V_\gamma$, we assume that IV relation is a straight line with slope of $\frac{1}{r_f}$, where r_f is the forward bias resistance.

For $V_D \geq V_\gamma$, we assume that IV relation is a straight line with current value to be zero.

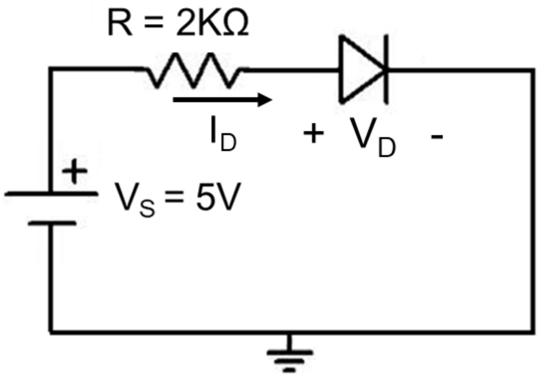
Using piecewise linear model, we can approximate diode as a combination of a voltage source of V_γ, a resistance of r_f and an ideal diode.





Diode models for DC analysis

For more accurate analysis of a diode circuit we use either iteration or graphical techniques. To understand these techniques lets consider a simple diode circuit consisting of a voltage source and a resistance.



Now if we apply KVL to the circuit, we get

$$V_S = I_D R + V_D$$
$$\Rightarrow \; I_D = \frac{V_S}{R} - \frac{V_D}{R}$$

We also know that the ideal IV characteristic of a diode is given as

$$I_D = I_S \left[e^{\left(\frac{V_D}{V_T}\right)} - 1 \right]$$

Here we are considering $\eta = 1$, for simplicity.
By comparing the above two equations we get:

$$V_S = I_S R \left[e^{\left(\frac{V_D}{V_T}\right)} - 1 \right] + V_D$$

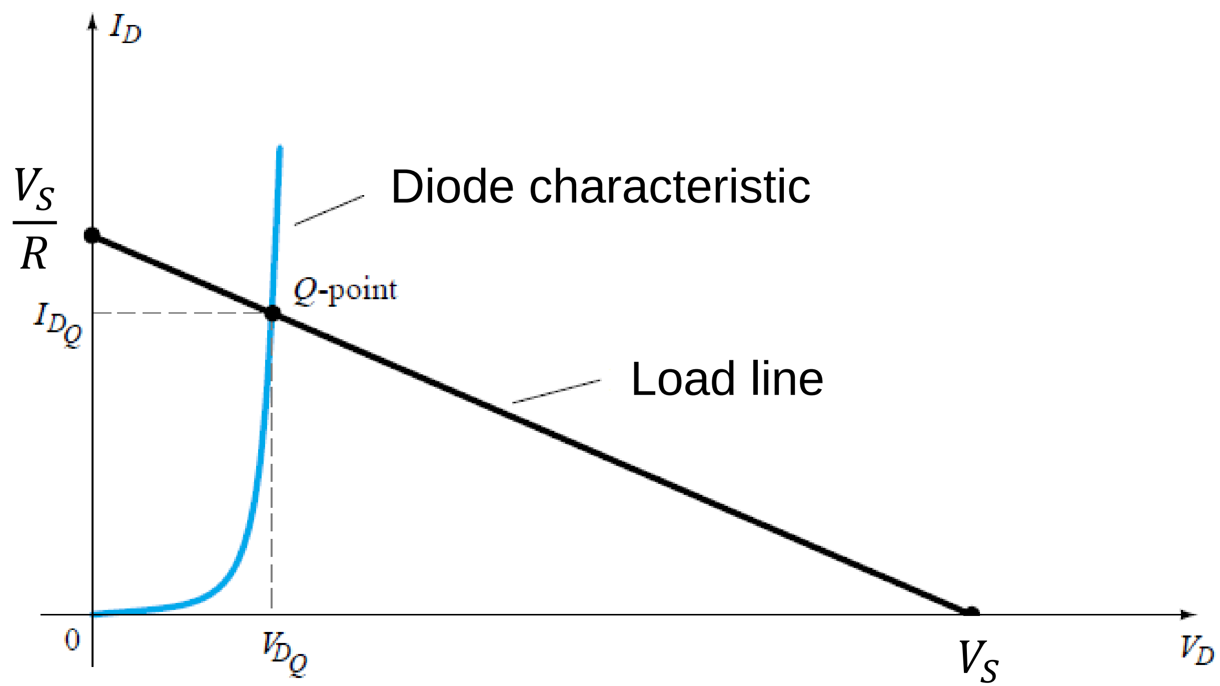
In this equitation although there is only one unknown (i.e. V_D), this can not be solved directly. This transcendental equation can be solved by using an iterative method. The solution to this equation is V_D=0.619V (as discussed in the class).

Diode models for DC analysis

The same problem can be solved graphically as well. For that lets consider the KVL equation again.

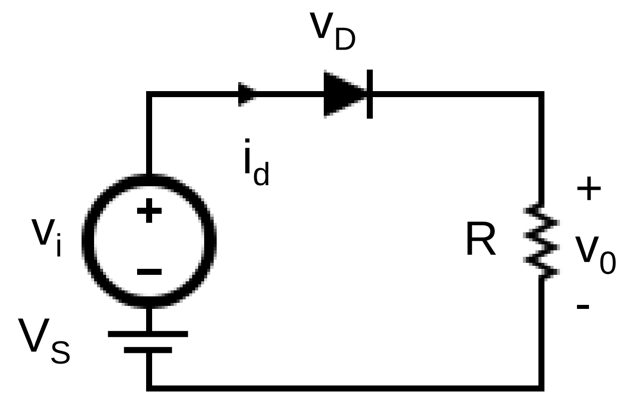
$$I_D = \frac{V_S}{R} - \frac{V_D}{R}$$

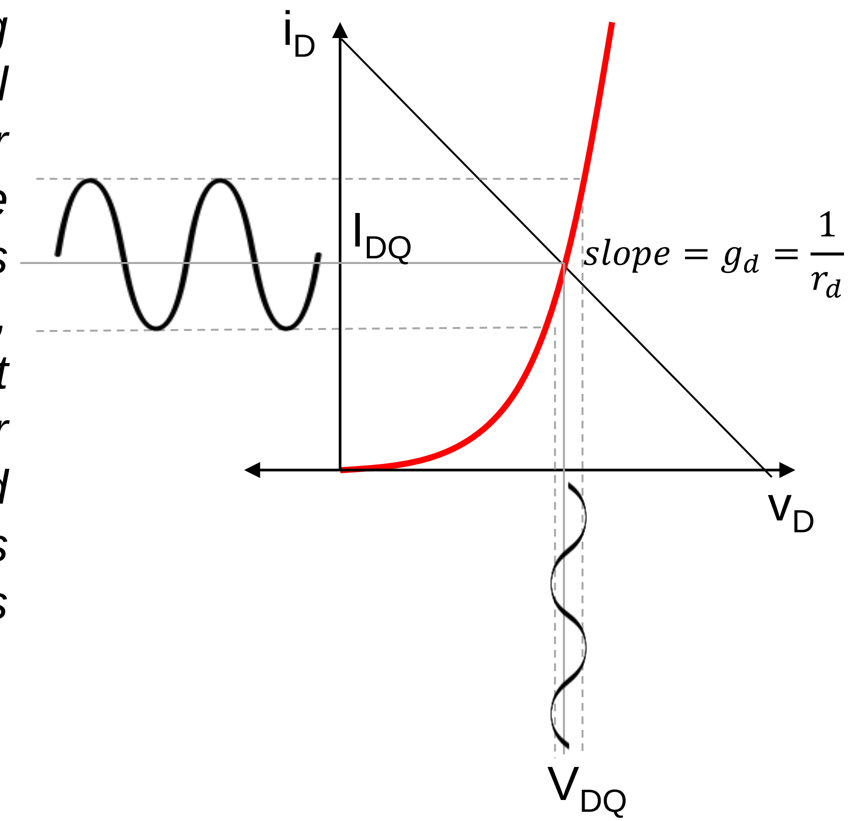
Since Vs and R are constants, this is a linear relationship between I_D and V_D. This equation is referred to as the load line of the circuit. When this equation is plotted along with the ideal diode equation on the same graph, the intersection between the two curves gives us the solution (i.e. the values of V_D and I_D). This intersection point is know as quiescent point or simply Q-point.



AC analysis of diode circuits

So far we have restricted our discussion to DC characteristics of a diode. However, diodes are also used in circuits where signals are time-varying, for example in a amplifier circuit, where the signal is time varying. In such situation we not only need the DC behaviour of a diode but also how they behave under time varying signal. Let us consider the following circuit, where along with the dc voltage source a time varying signal is also added to the circuit. We also consider here that the ac signal is much smaller than the dc bias voltage. Since the input voltage contains a dc component superimposed with an ac signal, the diode current will also have a dc component with an superimposed ac component. If a linear relationship is expected between the voltage and current, the operating point or the Q-point is chosen in the linear part of the diode IV curve, as shown.





AC analysis of diode circuits

If the Q-point is away from the origin, we can approximate the diode current by neglecting the -1 term, as

$$i_D \cong I_S e^{\left(\frac{v_D}{V_T}\right)} = I_S e^{\left(\frac{v_{DQ}+v_d}{V_T}\right)}$$

Where, V_{DQ} is the voltage at Q-point and v_d is the ac component. If the ac signal is much smaller than V_T, we can write

$$e^{\left(\frac{v_d}{V_T}\right)} \approx 1 + \frac{v_d}{V_T}$$

We can also write:

$$I_{DQ} = I_S e^{\left(\frac{V_{DQ}}{V_T}\right)}$$

Therefore,

$$i_D = I_{DQ}\left(1 + \frac{v_d}{V_T}\right) = I_{DQ} + \frac{I_{DQ}}{V_T} v_d = I_{DQ} + i_d$$

The relationship between the ac component of diode voltage and current is:

$$i_d = \left(\frac{I_{DQ}}{V_T}\right) v_d = g_d v_d$$

or

$$v_d = r_d v_d$$

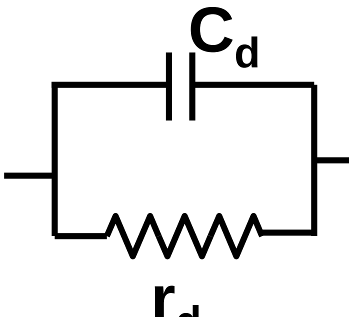
g_d and r_d are known as diode small-signal incremental conductance and resistance.

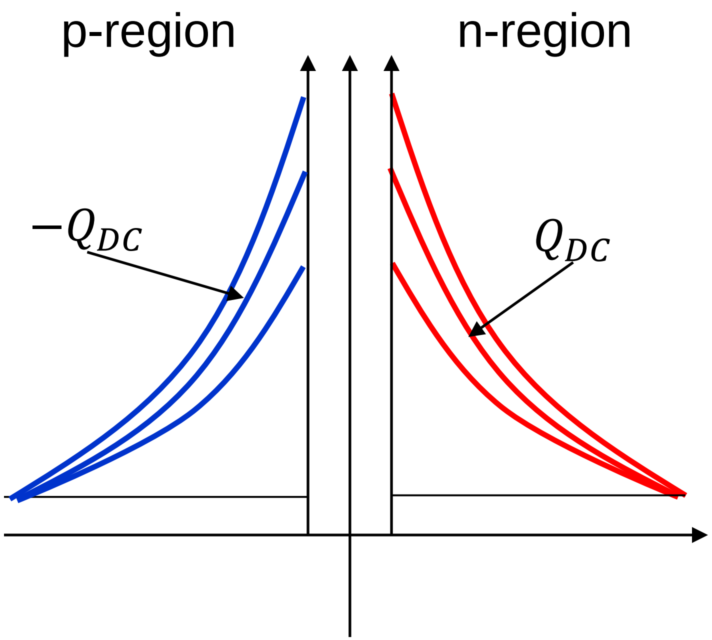
AC analysis of diode circuits

For ac analysis, along with diode resistance, we also need to take into account any capacitive effect that may appear due to change in charge accumulation near the depletion region. We have already discussed about junction capacitance when the diode is in reverse bias. Even for forward bias, a capacitive effect arises due to the fluctuation of the minority carrier concentration on both sides of the pn junction. As the diode voltage fluctuates between $V_{DQ} \pm \frac{v_d}{2}$, *the minority charge concentration on both side of the depletion region also fluctuates between* $Q_{DQ} \pm \Delta Q$. *This charge variation as a function of voltage can be considered as a capacitance and this capacitance is called a diffusion capacitance and expressed as*

$$C_d = \frac{dQ}{dV_D}$$

Once the diffusion capacitance is taken into account, the ac equivalent circuit for diode can be shown as:





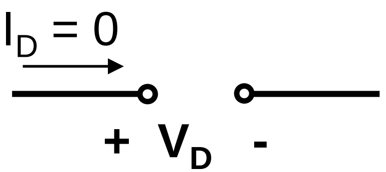
Diode Circuits

In this section we will discuss how diodes are used in various applications:

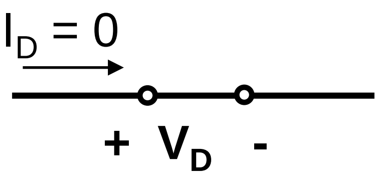
1. *Rectifier circuit (AC to DC conversion)*
2. *Voltage reference circuits (using Zener diodes)*
3. *Clipper circuit (used for voltage regulation into an electronic system)*
4. *Clamper circuit (used as base line stabilizer)*
5. *Logic gates*

We will analyse these circuits with two different diode models:

1. *Idealized diode model*

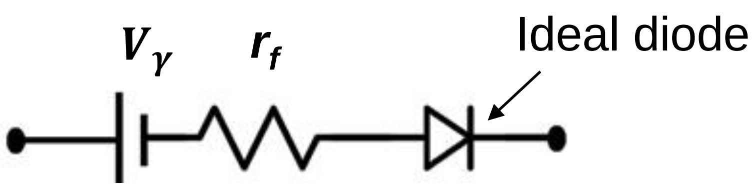


$V_D<0$, $I_D=0$



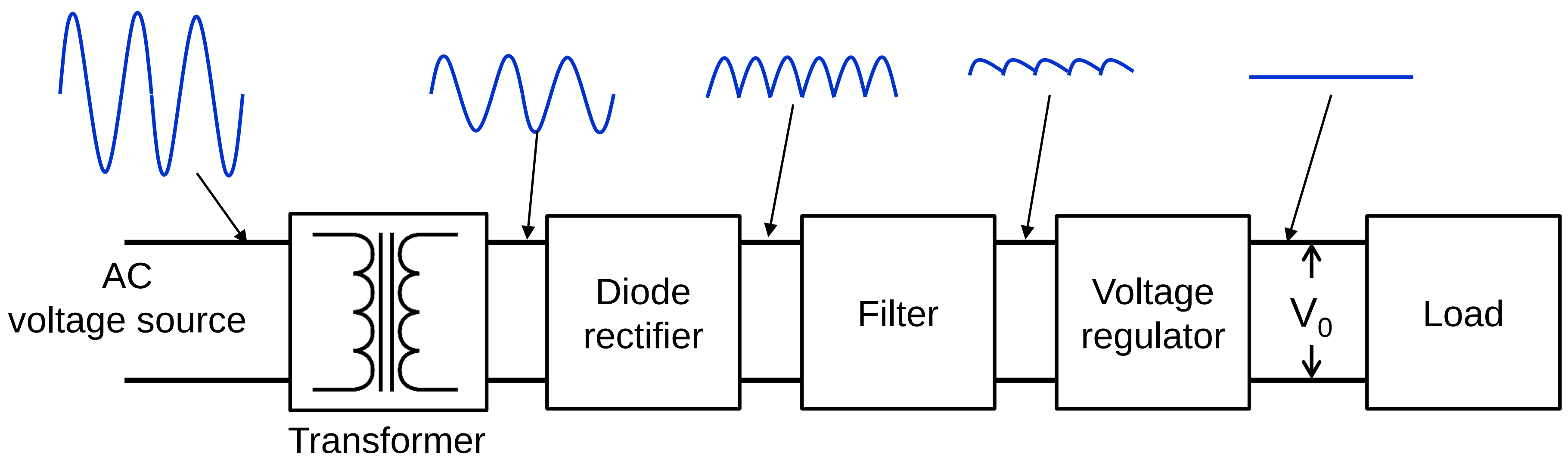
$I_D>0$, $V_D=0$

2. *Piecewise linear model*



DC power supply

Rectifier circuits are mainly found in DC power supplies. DC power supplied are required for all the electronic devices and the output voltage required from a DC power supply may range from 3V to 24V, depending on applications. For example, Laptops require about 19V and mobile phones run on about 4V. However, the voltage that we get from our plug point is an AC voltage with V_{rms}=230V at a frequency of 50Hz. So a DC power supply converts this AC signal into a DC signal with desired voltage. The different components of a DC power supply is shown below. The transformer first steps down the AC line voltage to a desired AC voltage. The rectifying circuit then converts the ac signal into a single polarity time varying signal. The ac component of the output voltage from the rectifying circuit is then removed by using a filter. Finally the voltage regulator provides a constant dc voltage to the load.



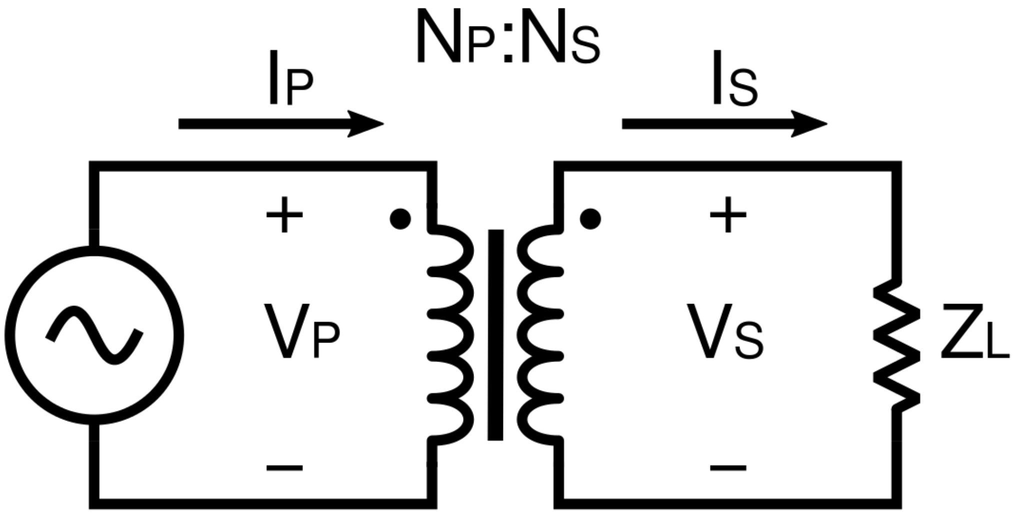
DC power supply

Transformer

For a transformer, the relationship between the primary and secondary voltage is given by:

$$\frac{v_P}{v_S} = \frac{N_P}{N_S}$$

Depending upon the transformer turn ratio, the voltage can be stepped up or stepped down.



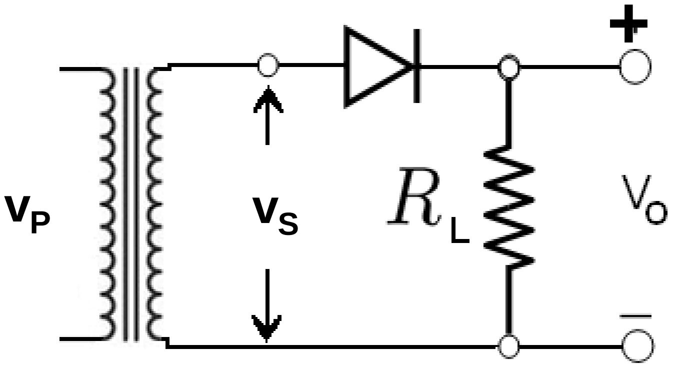
Rectifier

Once the voltage is stepped down from the line voltage the next process it goes through is called rectification. Now there are two ways rectification can be done:

1. *Half wave rectification*
2. *Full wave rectification*

Half-wave Rectifier

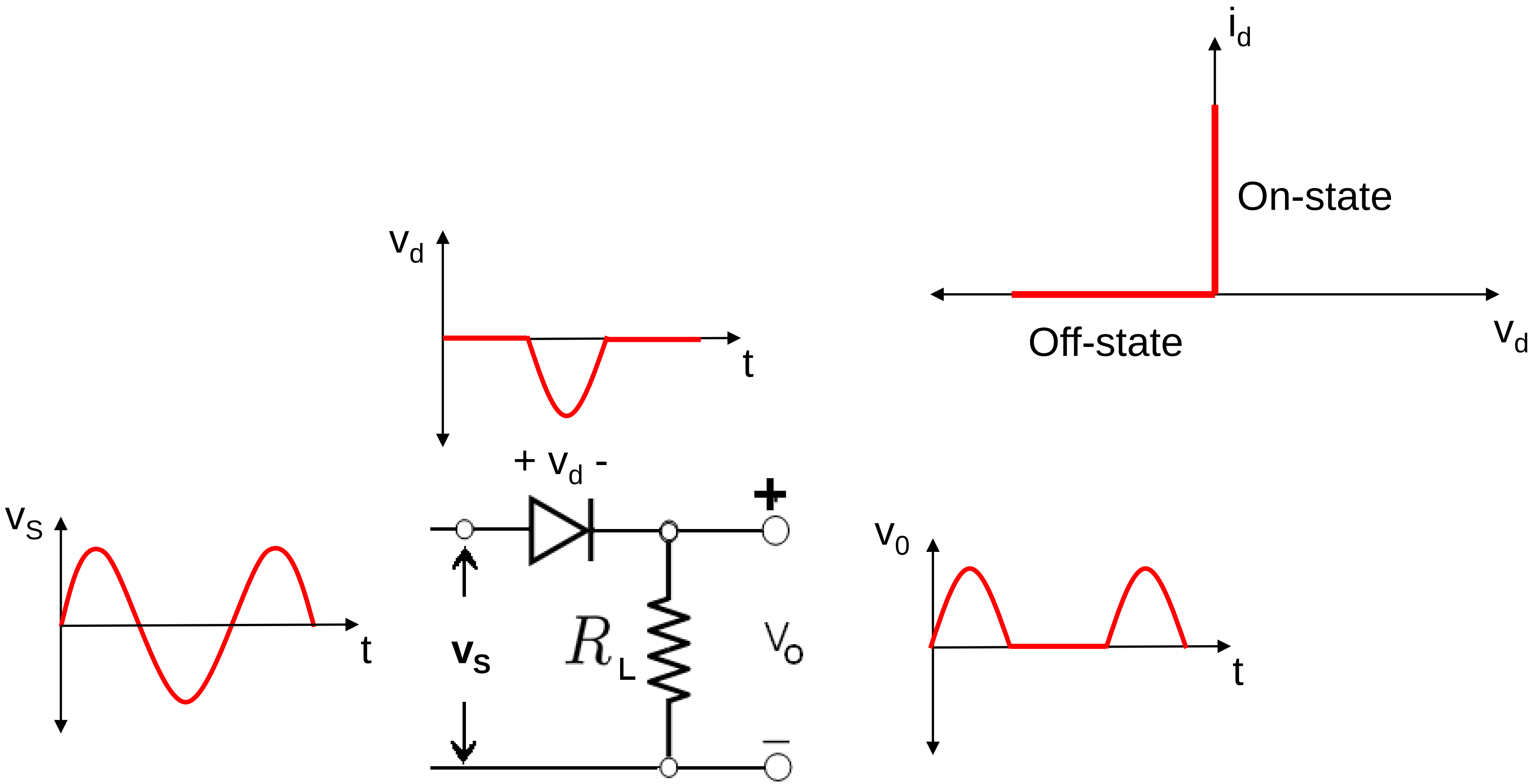
The circuit diagram of a half-wave rectifier is shown in the figure. The circuit consists of a diode in series with the load resistance, R_L (in our example, which is basically the input resistance of the remaining components of the DC power supply).



To analyse this circuit we will first use the idealized diode model and then piece wise linear model.

Half-wave Rectifier

Lets consider that the secondary voltage of the transformer v_s, is sinusoidal (which is usually the case). If we now use the idealized diode model, then for positive cycle of v_s the diode will be 'on' and all the voltage will drop across the load and for the negative half cycle the diode is 'off' so all the voltage drop will occur at the diode terminal. This is pictorially represented in the following figure.



Half-wave Rectifier

Once we understood the operation of a half-wave rectifier using the simple idealized diode model, here we will use the piece-wise linear model. Here the diode will be replaced by a voltage source, a resistance and a ideal diode in series.

Since now we have a voltage source (V_γ) opposing the applied ac voltage (v_s), unless v_s is greater than V_γ no current will flow through the circuit. If we consider the input voltage as $v_s = V_s sin\omega t$, then for $v_s > V_\gamma$, the current through the circuit is:

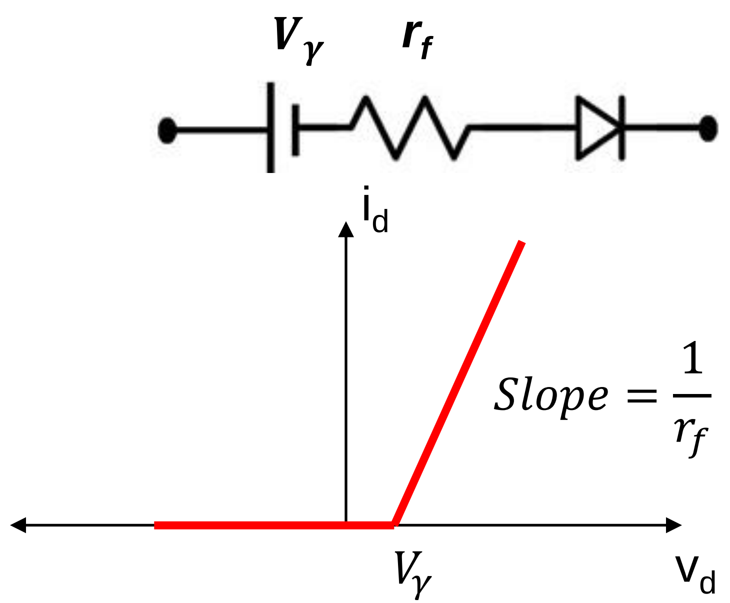
$$i_d = \frac{V_s sin\omega t - V_\gamma}{R_L + r_f}$$

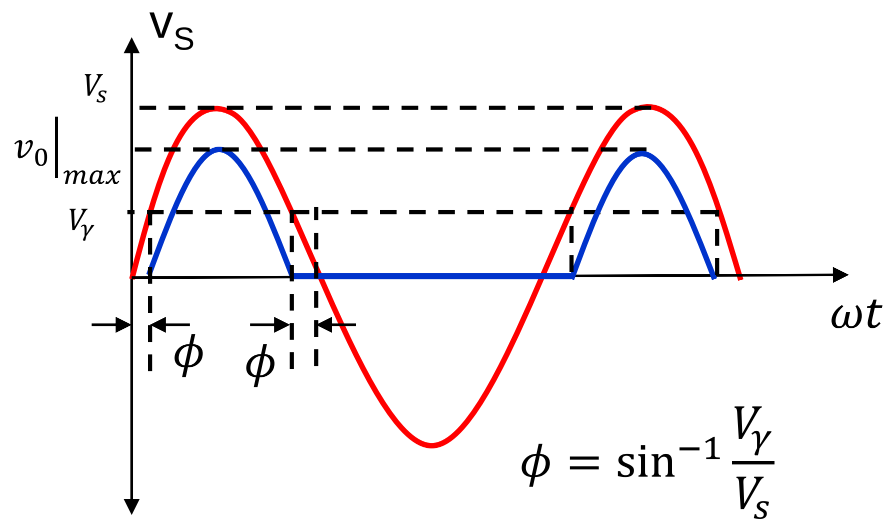
And the voltage drop across the load is:

$$v_0 = \frac{V_s sin\omega t - V_\gamma}{R_L + r_f} R_L$$

Therefore the maximum output voltage is:

$$v_0\Big|_{max} = \frac{V_s - V_\gamma}{R_L + r_f} R_L$$





Can you draw the voltage across the diode

Half-wave Rectifier: Example

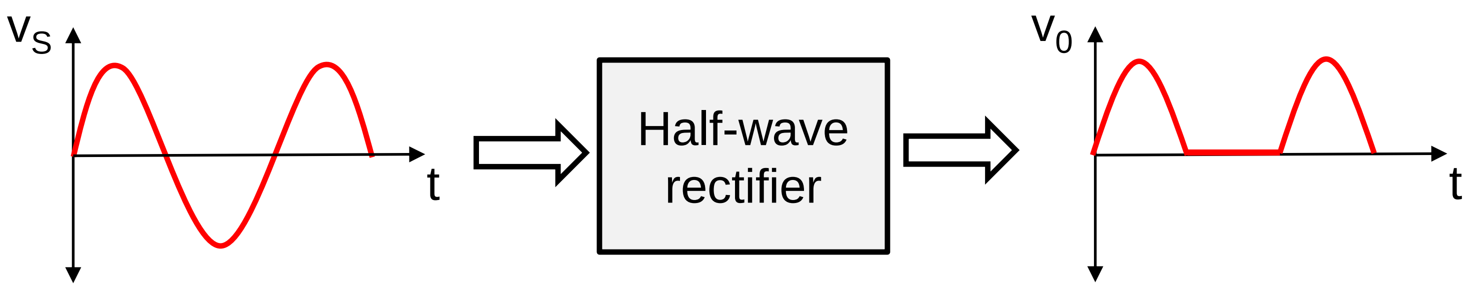
Let us consider the following circuit, where a half-wave rectifier circuit is used to charge a battery. The battery has a voltage of 12V and the series resistance of the half-wave rectifier circuit is 100Ω and the diode has a cutin voltage of 0.6V. The supplied ac voltage is $v_s(t) = 24\sin(\omega t)$. Assume that $r_f = 0$.
Determine the peak diode current, maximum reverse-bias diode voltage and fraction of the cycle over which the diode is charging.
Ans: 114mA, v_R=36V, 32.4%

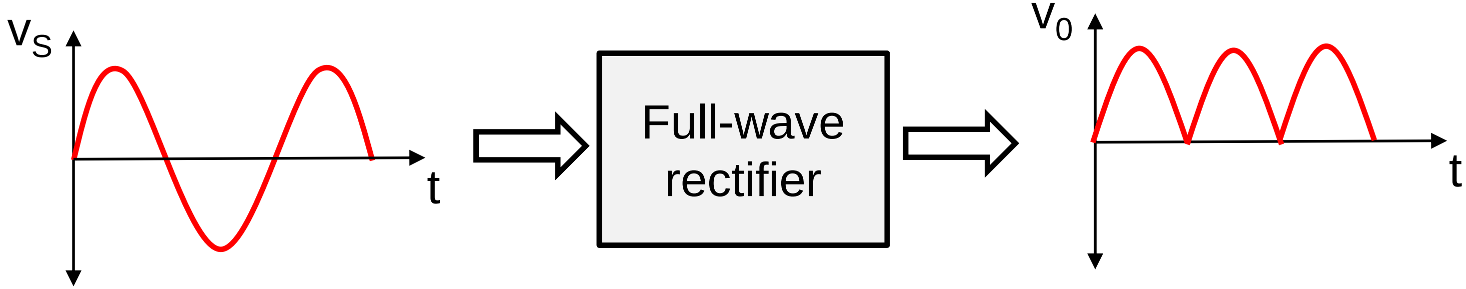
This example shows that the battery is charging only for 32.4% of the total cycle. This means that the efficiency of this charger is quite low.

Full-wave rectifier

Although half-wave rectifier circuit can convert the ac voltage to a single polarity voltage, the voltage at the load is available only for positive half-cycle. Therefore during the negative half-cycle the power is not transferred to the load. Full-wave rectifier circuits address this issue by allowing current to flow through the load both positive and negative half cycles. There are two commonly used full-wave rectifier designs:

1. *Full-wave rectifier using Center-tapped transformer*
2. *Full-wave bridge rectifier*

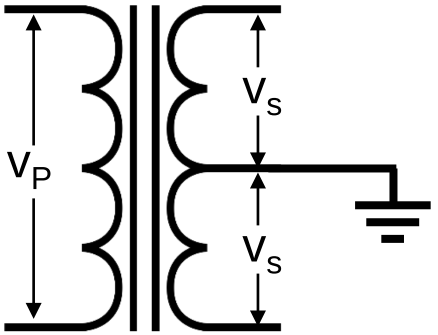




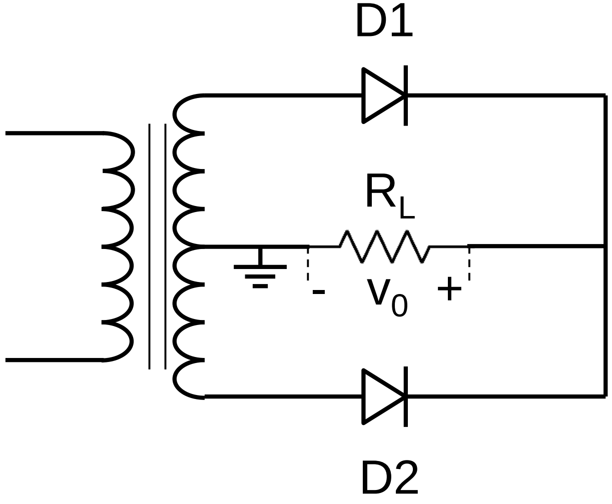
Full-wave rectifier

1. ***Full-wave rectifier using Center-tapped transformer:***

In a center-tapped transformer, the primary winding connected to the ac source has N_1 turns, and each half of the secondary windings has N_2 turns. An image of a center-tapped transformer is shown in the figure.

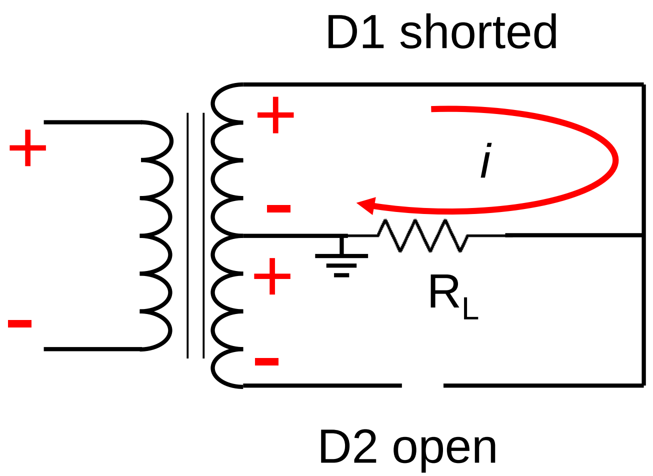


The circuit for a full-wave rectifier using the center-tapped transformer is shown below. For the positive cycle, diode D1 is on and diode D2 is off. Hence the current only exists in the loop consisting of D1. for the negative cycle, on the other hand, D2 is on and D1 is off and the current flows in the loop consisting of D2. However, in both cases the direction of current through the load remains the same. As a result we get an unipolar voltage across the load for the full cycle of the input voltage.

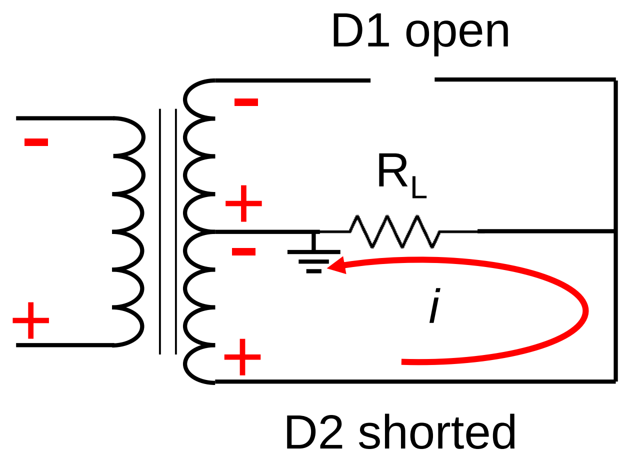


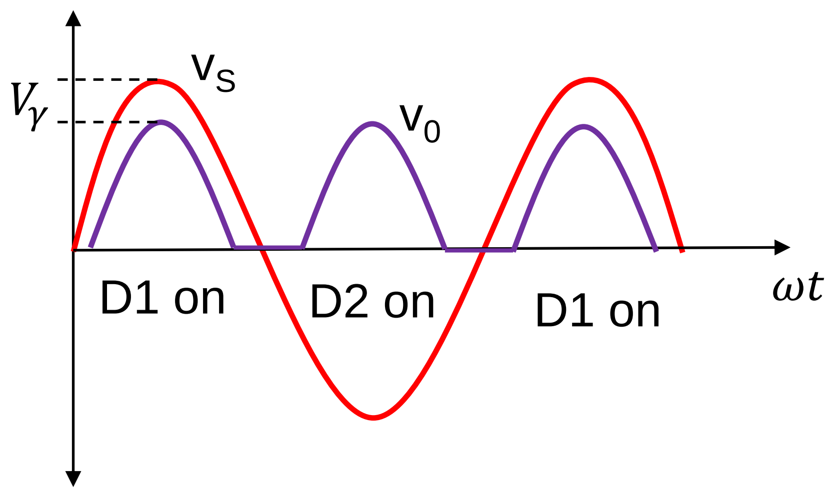
Full-wave rectifier

For positive cycle



For negative cycle



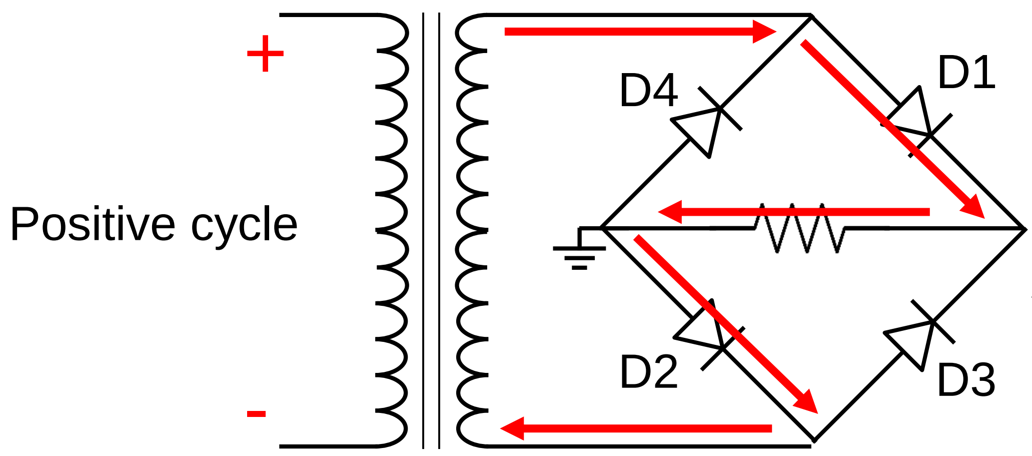


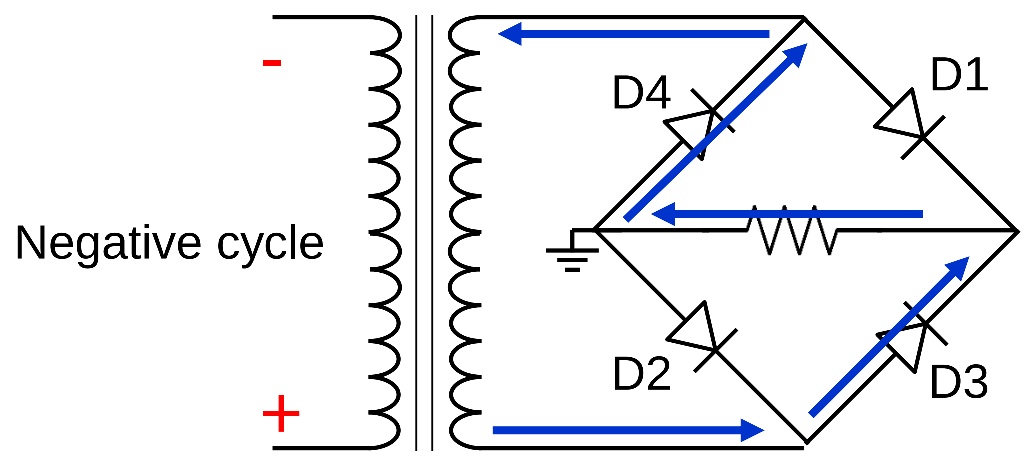
What will be the voltage across each diode as a function of time.
What is the PIV of each diode?

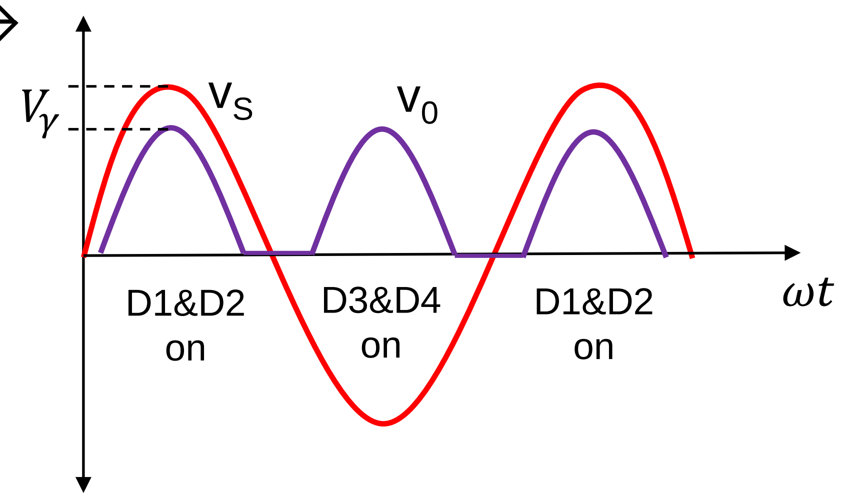
Full-wave rectifier

1. Full-wave bridge rectifier:

The circuit of a bridge rectifier is shown below, which uses 4 diodes.



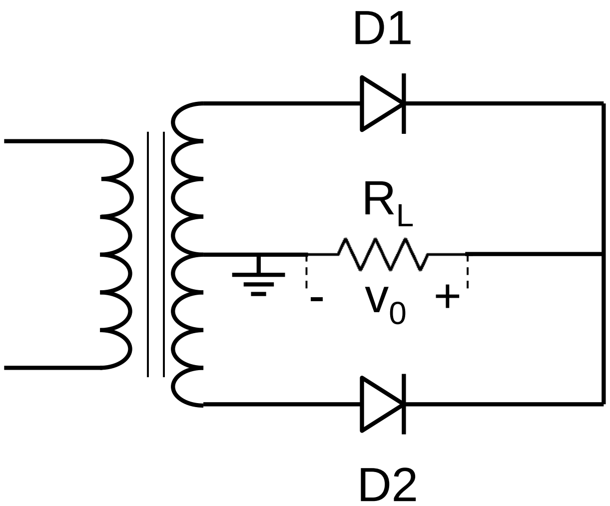


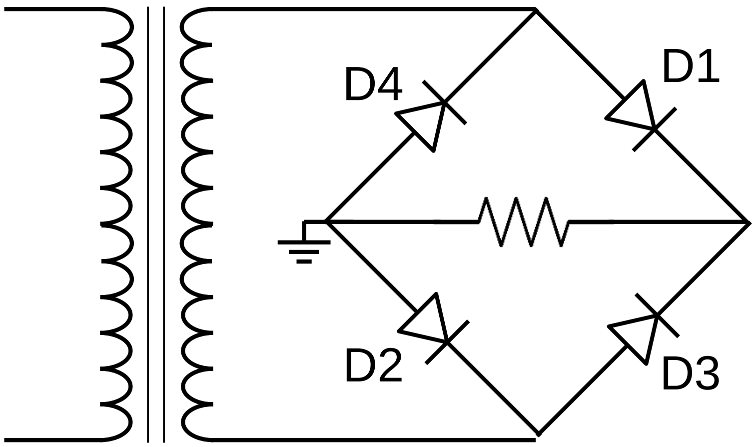


What will be the voltage across each diode as a function of time?

What is the PIV of each diode?

Full-wave rectifier





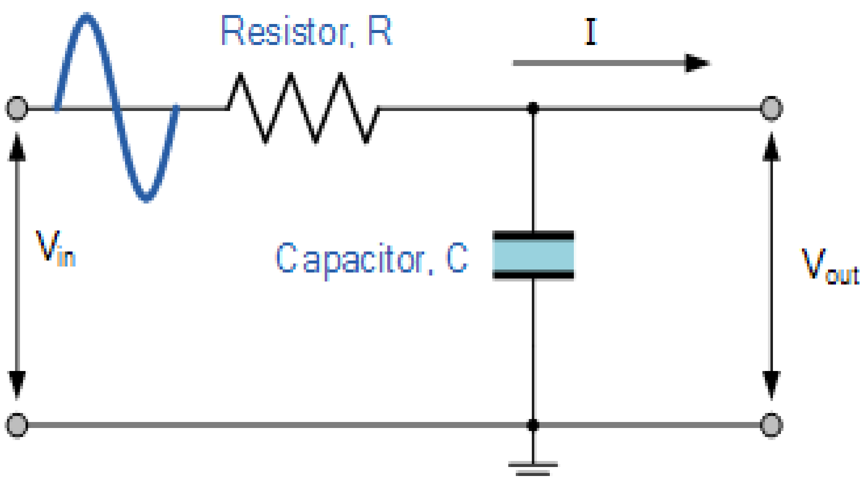
Advantage of center-tapped over bridge rectifier: for the center-tap rectifier the output voltage is $v_0 = V_s - V_\gamma$. Whereas for bridge rectifier $v_0 = V_s - 2V_\gamma$. Also number of diodes required is less.
However, in bridge rectifier only half as many turns are required for the secondary winding in comparison to center-tapped rectifier.
Another major advantage of bridge rectifier is that the peak inverse voltage that any diode must sustain without break down is only half that of the center-tap rectifier.

As a result, bridge full-wave rectifiers are preferred over center-tapped full-wave rectifiers.

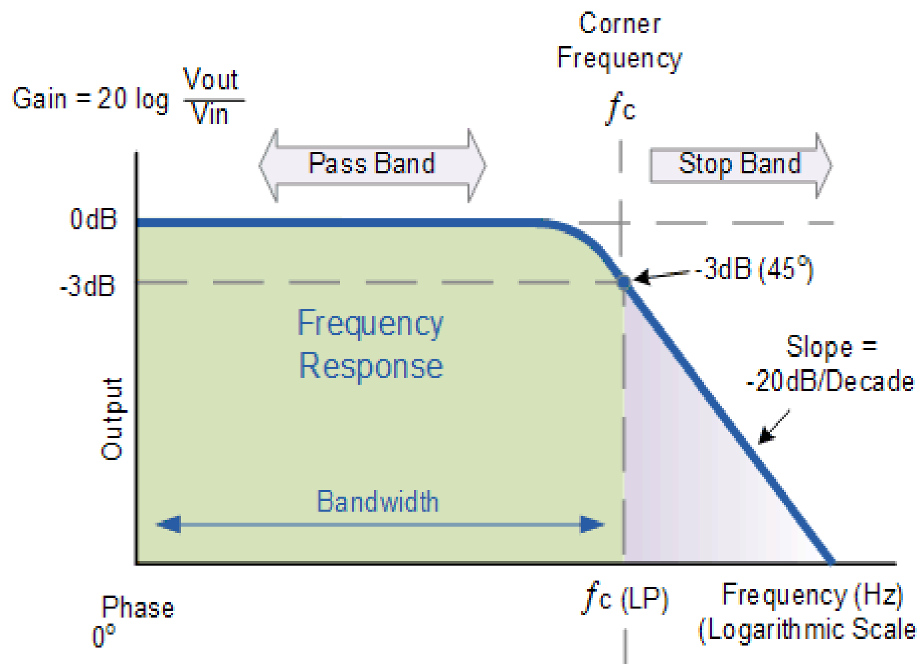
Filters

It should be obvious from the previous discussions that the rectifier converts an ac signal with zero dc value to a single polarity time varying voltage signal with non-zero dc value. However, the output of a rectifier still contains a large amount of frequency components. A filter is added at the output terminal of the rectifier circuit to remove these frequency components. As out interest is to retain only the dc component and remove any time varying component from the voltage signal, we should use a low pass filter at the output of a rectifier.

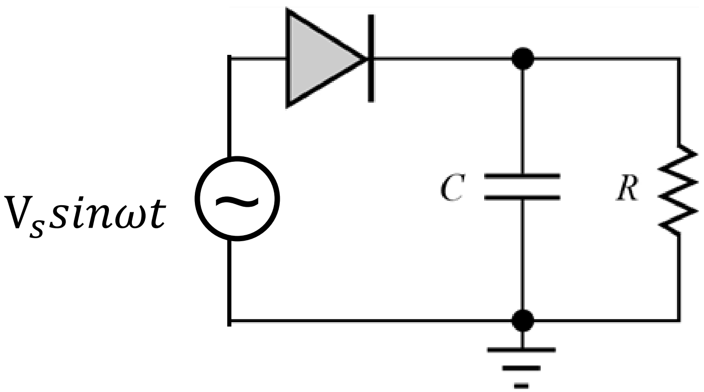
Here we will use a first-order RC circuit to demonstrate the filtering operation.

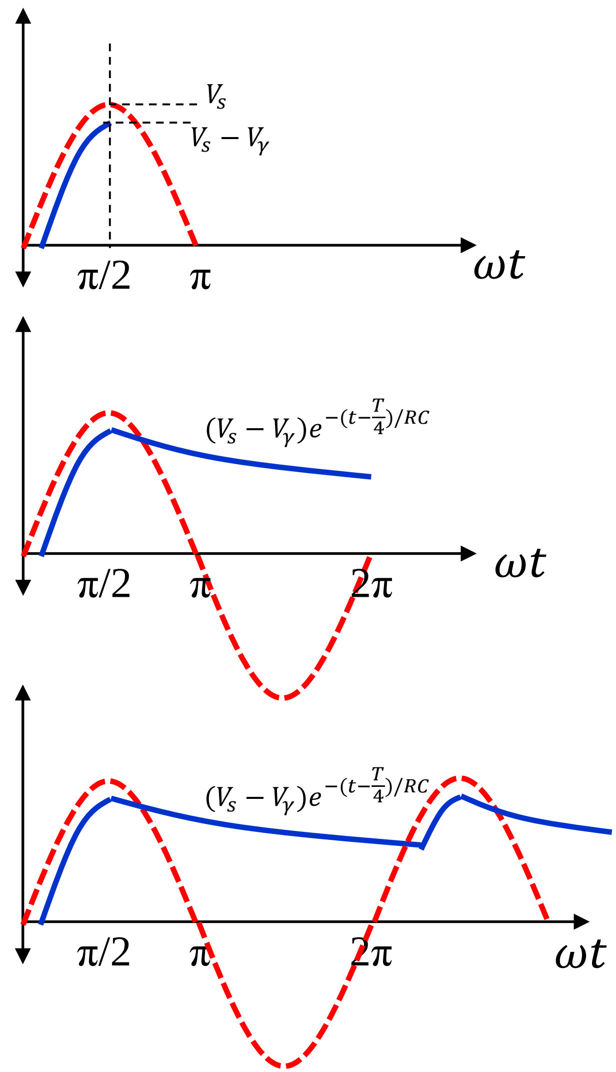


$$V_{out} = \frac{1}{j\omega RC + 1} V_{in}$$



Half-wave rectifier with Filter





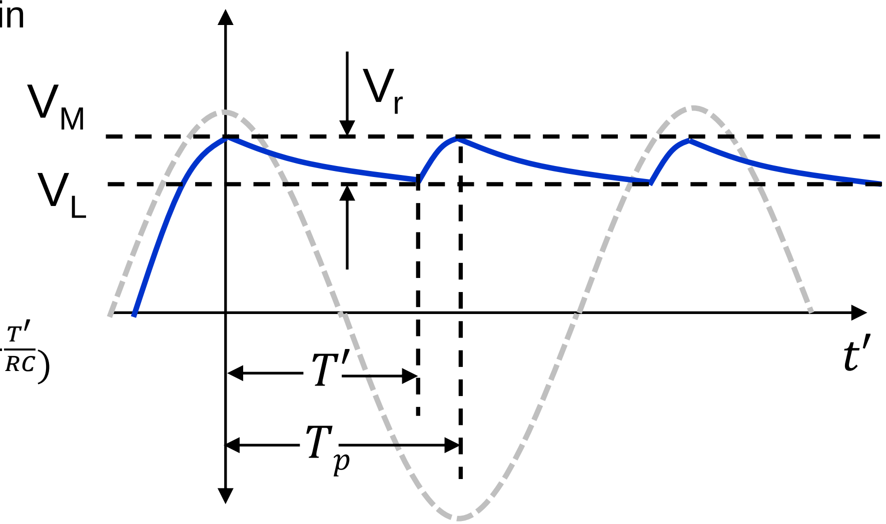
In the first quarter cycle the capacitor will be charged by the applied voltage through the diode. If we consider the r_f = 0, then the charging will be instantaneous and the voltage across the capacitor will follow the input voltage.

Once input voltage reaches its peak and begins to decrease, the diode goes into reverse bias and becomes an open circuit. In such situation the capacitor starts to discharge through the load resistance. The discharging happens exponentially with a time constant of RC. For all the time when the capacitor voltage is more than $v_s - V_\gamma$, the diode is off.

If the RC constant is large enough that the capacitor does not completely discharges when the next positive cycle starts, the diode remains off until $(V_s - V_\gamma)e^{-\frac{t-\frac{T}{4}}{RC}} + V_\gamma > v_s$.

Full-wave rectifier with Filter

Output waveform of a full-wave rectifier with capacitive filter:



Du to the discharging of the capacitor we get a ripple effect in the filtered voltage waveform.

The largest output voltage is $V_M = V_s - V_\gamma$

The smallest output voltage is $V_L = V_M e^{-T'/RC}$

The ripple voltage V_r is defined as $V_r = V_M - V_L = V_M(1 - e^{-\frac{T'}{RC}})$

Since we want the discharging of the capacitor to be small, $T' \ll RC$.
Therefore, we can write V_r as

$$V_r = V_M\left(\frac{T'}{RC}\right)$$

We can further approximate that $T' \approx T_p$. Since T_p is between two peak values, for full wave rectifier, $T_p = {}^1/_{2f}$, where *f* is the frequency of the signal. So the ripple voltage is

$$\boxed{V_r \approx \frac{V_M}{2fRC}}$$

For a half-wave rectifier

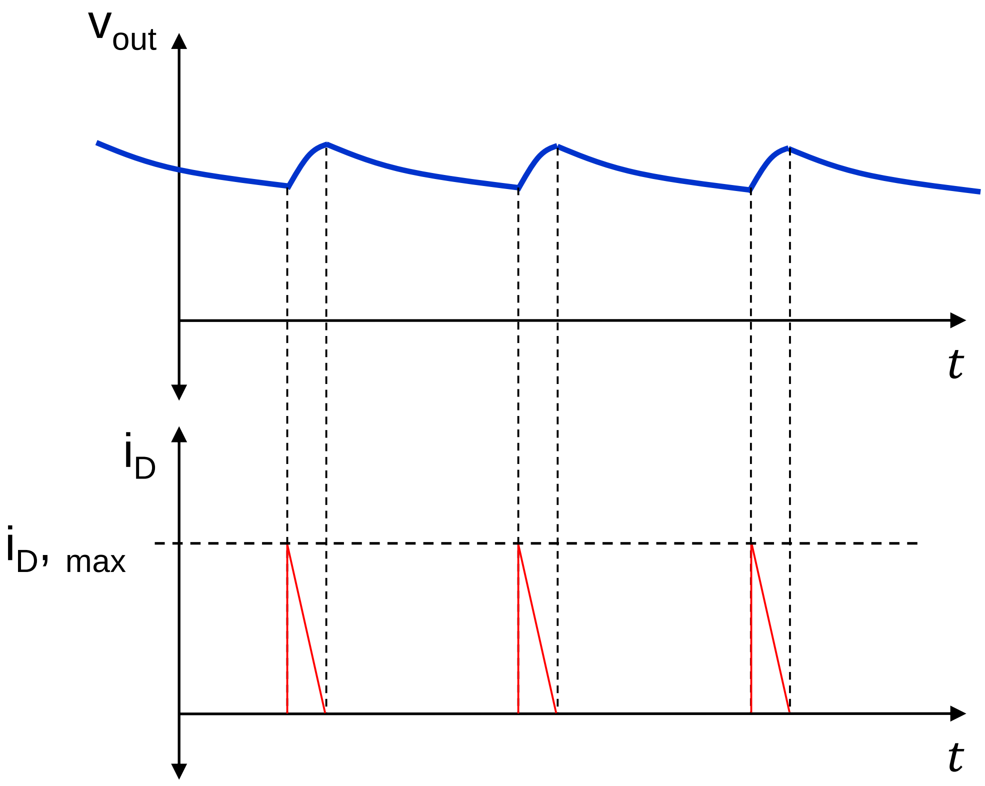
$$\boxed{V_r \approx \frac{V_M}{fRC}}$$

Full-wave rectifier with Filter

Current through the diode:

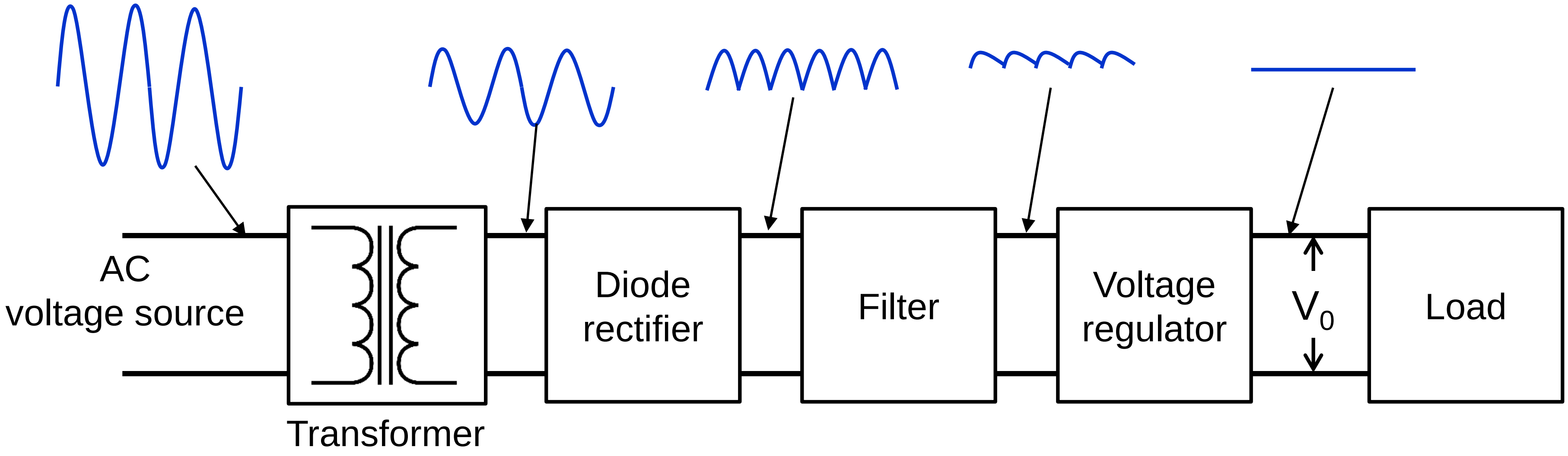
$$i_{D,max} \cong \frac{V_M}{R}\left(1 + \pi\sqrt{\frac{2V_M}{V_r}}\right)$$

$$i_{D,avg} \cong \frac{1}{\pi}\sqrt{\frac{2V_r}{V_M}}\frac{V_M}{R}\left(1 + \pi\sqrt{\frac{2V_M}{V_r}}\right)$$



Voltage regulator

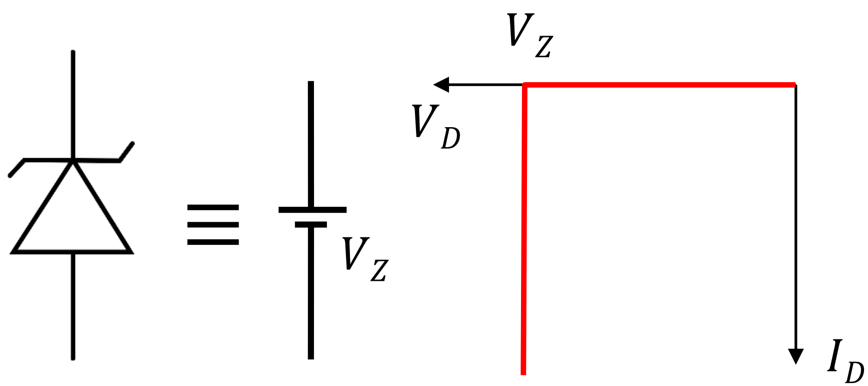
The rectifier-filter combination significantly reduces the ac component of the input signal. However, as we can see there are still some ripples present in the output of the filter. To further remove the ac component of the signal make the output voltage of the DC power supply a pure DC voltage regulator are used. In this course we will study voltage regulator circuit using 'Zener diodes'.



Zener diode

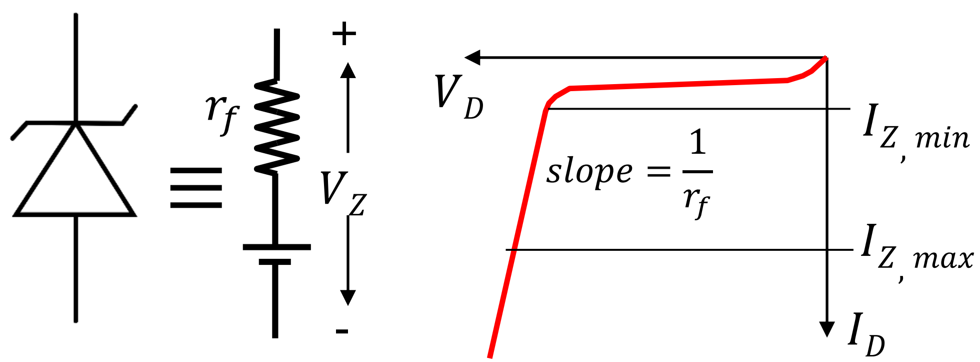
Because of the high doping levels in the n and p side of the diode, Zener diodes have relatively low reverse breakdown voltage in comparison to conventional diodes. In the previous lecture, we have already discussed the Zener breakdown process. Here we will be focusing on the operation of Zener break down to maintain steady voltage level, required for a voltage regulator. Figure shows the behaviour of a Zener diode. Since Zener diode are mainly used under reversed bias condition, only negative part of the iv relation is shown.

Equivalent circuit of an ideal Zener diode



In ideal Zener diode, as soon as the voltage across the diode becomes more than the Zener voltage (i.e. the break down voltage) the diode becomes short circuit while maintaining a fixed terminal voltage.

Equivalent circuit of a real Zener diode



In reality, Zener diodes have finite resistance after breakdown known as Zener resistance (of the order of few ohms). As a result, any change in the Zener current cause a slight change in the terminal voltage .

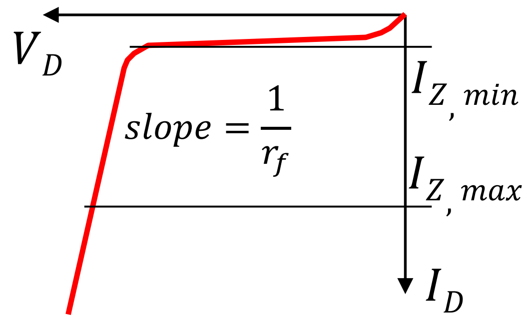
Zener diode

V_Z = Nominal Zener voltage

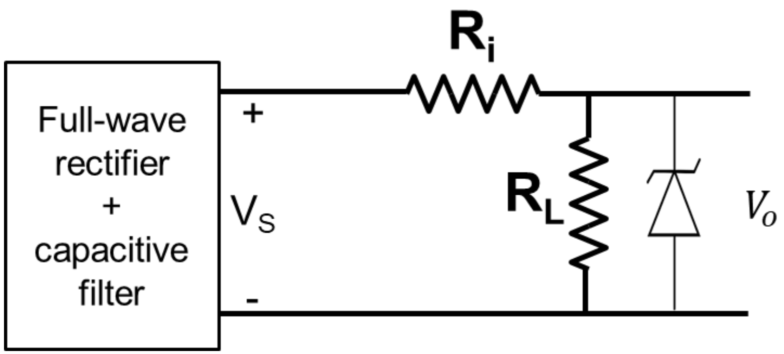
$I_{Z,min}$ = minimum dc current under Zener break down

$I_{Z,max}$ = maximum dc current under Zener break down

$P_{D,max} = I_{z,max} \times V_Z$ = maximum allowed power dissipation by the diode



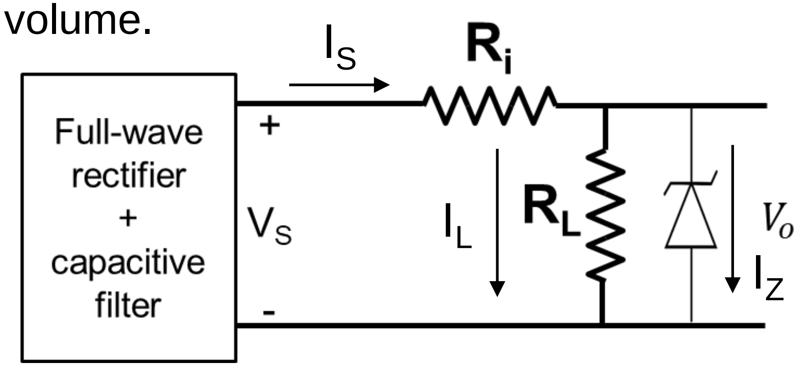
Below is a voltage regulator circuit using Zener diode.



In order to avoid excessive current flow through the Zener diode, a resistance R_i is put in series. In order to keep the Zener diode in break down while maintaining power dissipation below $P_{D,max}$, the maximum value of the input voltage is kept above Zener breakdown voltage, i.e. $V_{S,min} > V_Z$. And the current through the diode is kept within the range $I_{Z,max} > I_D > I_{Z,min}$

Zener diode as voltage regulator

Usually in a voltage regulator circuit, the input voltage varies over a specific range (V_M - V_L) and the load current may vary over a wide range. For example, the filtered output voltage of a rectifier circuit has a specific voltage ripple and a speaker phone as the load where zero current through the load means no volume and maximum current means full volume.



In the voltage regulator circuit, the voltage across the Zener diode can be found by using thevenin's theorem.

$$V_{th} = \frac{R_L}{R_L + R_i} V_i$$

If $V_{th} > V_Z$, then the diode is in the breakdown region. So we can write,

$$V_o = V_Z$$

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

$$I_S = \frac{V_s - V_z}{R_L}$$

$$I_Z = I_S - I_L = \frac{V_s - V_z}{R_L} - I_L$$

While designing a voltage regulator circuit, we need to consider two limiting cases:

a) When the I_L is maximum and V_S is minimum, the diode should still be in the break down region, i.e. the diode current should be $I_{Z,min}$.

b) When the I_L is minimum and V_S is maximum, the diode current should be $I_{Z,max}$. i.e. the power dissipation in the diode should not cross the maximum power rating.

If these two conditioned are satisfied we can ensure that for any other input voltage-load current condition the Zener diode will perform as intended.

Zener diode as voltage regulator

Therefore, we need to choose the value of R_i such that,

For $I_{Z,min}$,

$$R_i = \frac{V_{s,min} - V_Z}{I_{Z,min} + I_{L,max}}$$

For $I_{Z,max}$,

$$R_i = \frac{V_{s,max} - V_Z}{I_{Z,max} + I_{L,min}}$$

Equating the above equations we get,

$$[V_{s,max} - V_Z][I_{Z,min} + I_{L,max}] = [V_{s,min} - V_Z][I_{Z,max} + I_{L,min}]$$

If we know the range of the voltage and load current ranges, we can find out what should be the value of R_i.

Zener diode as voltage regulator

The output of a voltage regulator circuit consisting of an ideal Zener diode has a fixed terminal voltage, i.e. $V_o=V_Z$. As long as the diode is in breakdown region, the terminal voltage remains fixed irrespective of the load current.
However, in real Zener diode, due to finite resistance the voltage across the Zener diode varies, as a result the terminal voltage of the regulator will also vary.
There are two figure of merits defined for a voltage regulator.

a) Source regulation: defined as the change in the output voltage with a change in the source voltage.

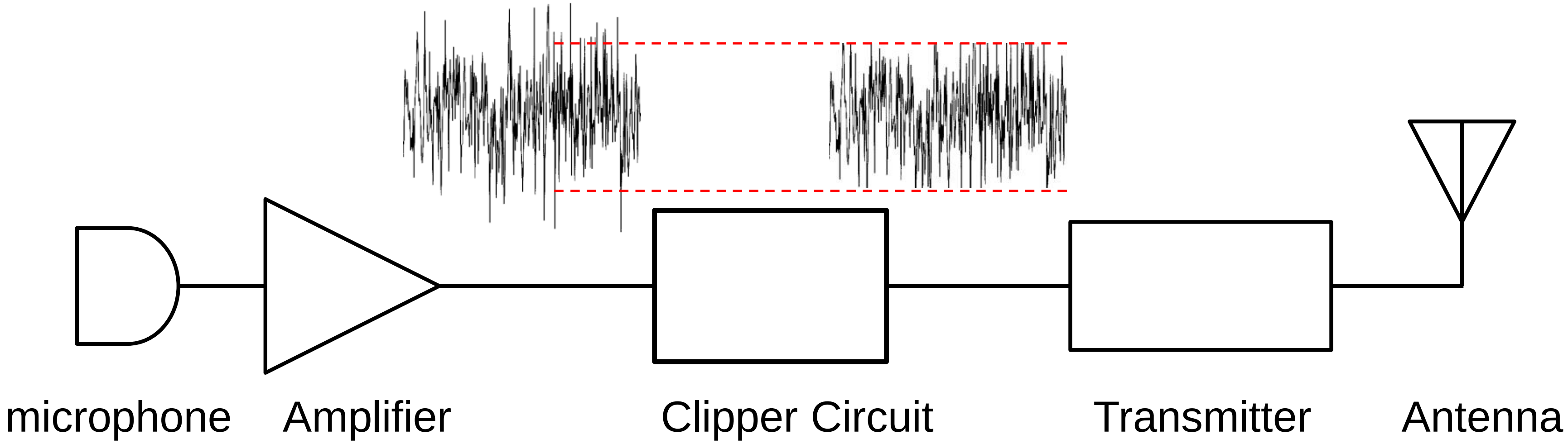
Source regulation $\equiv \frac{\Delta v_L}{\Delta v_S} \times 100\%$

b) Load regulation: defined as the change in output voltage with the change in the load current.

Load regulation $\equiv \frac{v_{L,no\ load} - v_{L,full\ load}}{v_{L,full\ load}} \times 100\%$

Diode clipper circuit

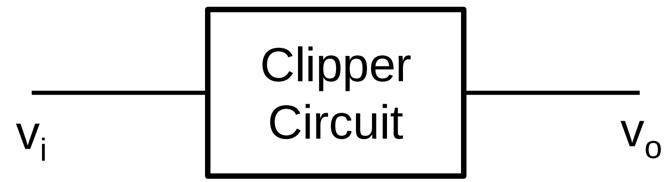
Clipper circuits are used to eliminate portions of a signal that are above or below a specified level. These are also called limiter circuits. One of the applications of a clipper circuit is in radio transmitter, where any excessive noise spikes above a certain level can be limited. Below a radio transmitter is shown with a clipper circuit. This is done to protect the transmitter and also to maintain linear operation of the transmitter.



Diode clipper circuit

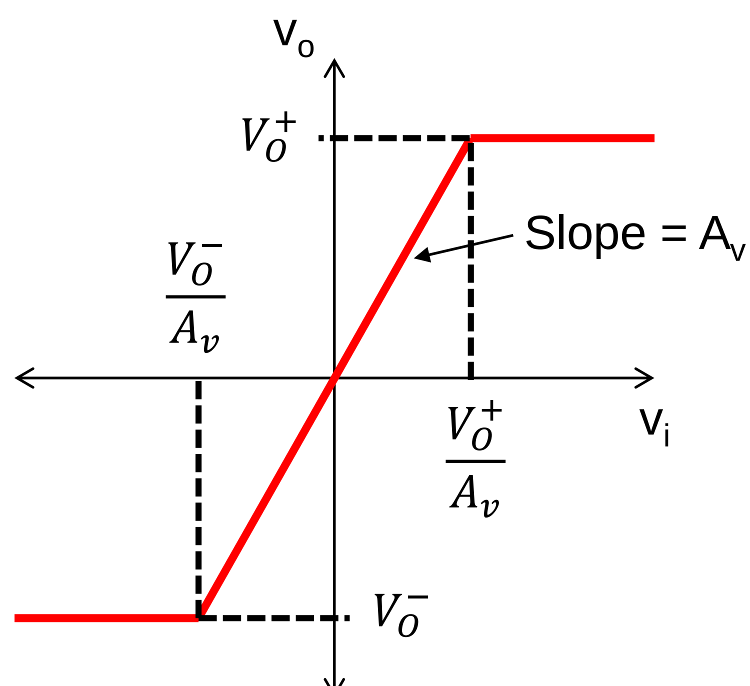
Figure below shows the general voltage transfer characteristics of a clipper circuit. Within certain input voltage limit, i.e. when $\frac{V_O^-}{A_v}$ < v$_i$ < $\frac{V_O^+}{A_v}$, $v_o = A_v v_i$. *If* v$_i$ < $\frac{V_O^-}{A_v}$, $v_o = V_O^-$ *and If* v$_i$ > $\frac{V_O^+}{A_v}$, $v_o = V_O^+$

When $A_v > 1$, *these circuits are called active clipper circuit. And when* $A_v \leq 1$, *these circuits are called passive clipper circuit.*



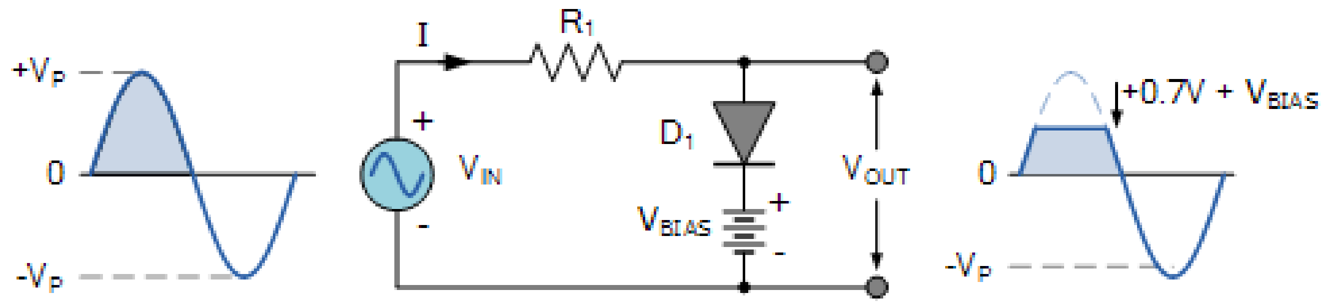
Passive clipper circuits use diodes and resistors, whereas active clipper circuits use amplifiers such as opamps.

In this lecture we will consider passive clipper circuits.

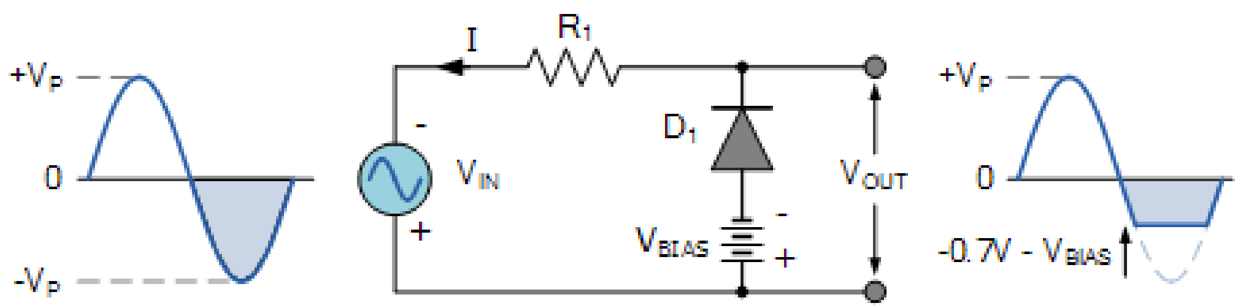


Diode clipper circuit : examples

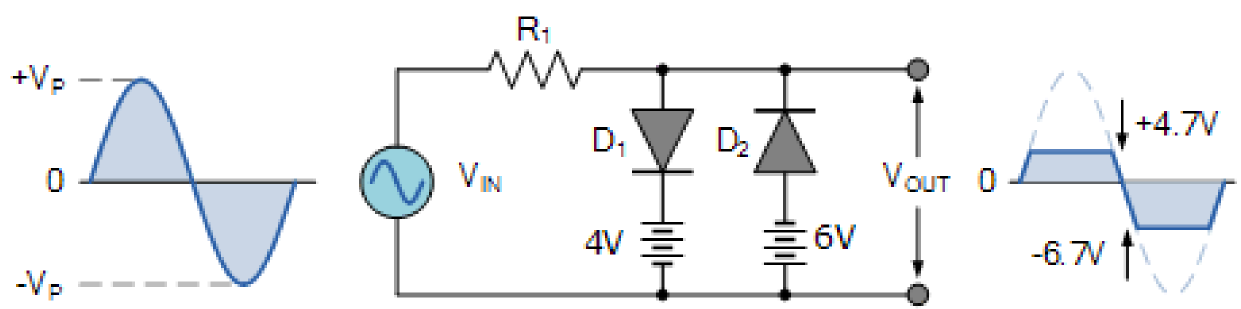
Positive voltage clipper



Negative voltage clipper

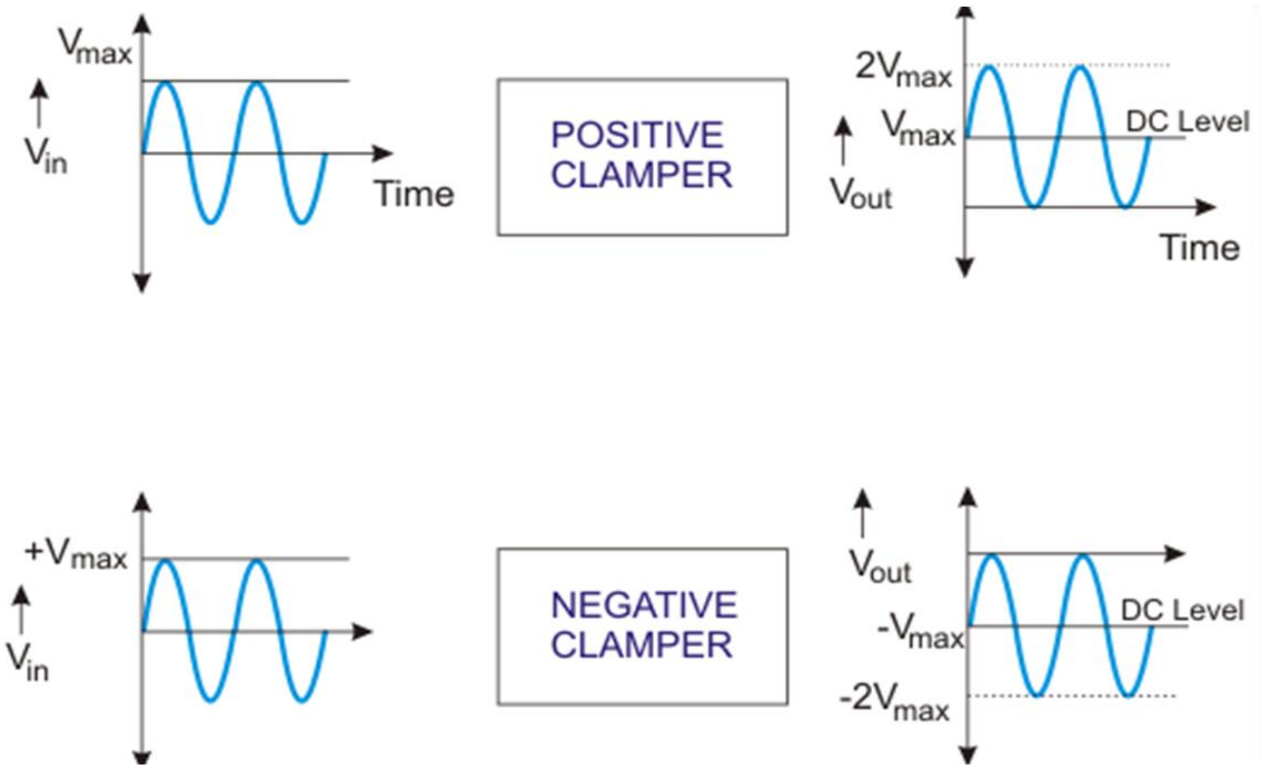


Negative+ positive voltage clipper



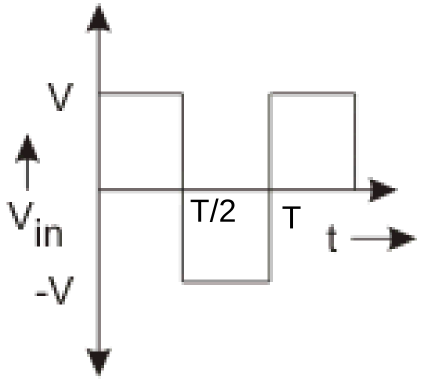
Diode clamper circuit

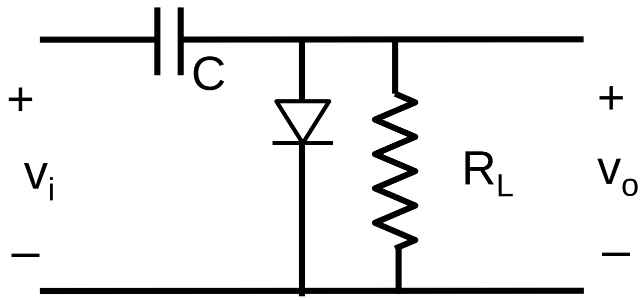
Clamper circuits are used shift the dc level of an ac signal. Since the positive or negative peak of a signal can be positioned at the desired level by using the clamping circuits, it is also called as level shifter.



Diode clamper circuit

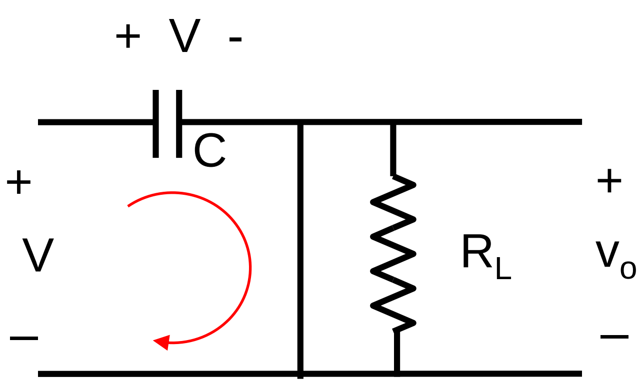
Below is a clamper circuit, where a input signal is applied to a load resistance via a capacitor and a diode. Operation of a clamper circuit can be best understood using a square wave form.





Considering ideal diode, i.e. r_f=0 and V_γ=0

For 0<t<T/2, v_i=+V
As we apply KVL we can se that the diode is forward biased. So short circuited.

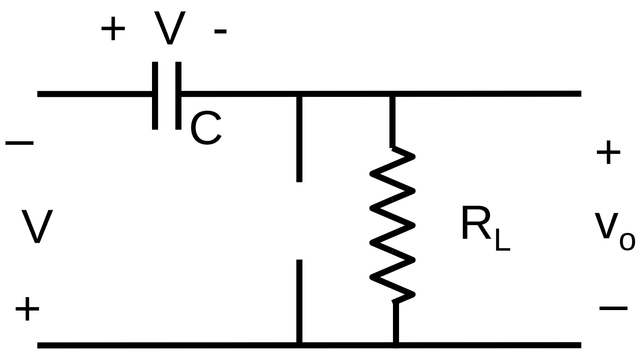


Also we can notice that since rf=0, the capacitor will be charge instantaneously to +V. Hence the voltage across the load resistance is 0.

Diode clamper circuit

For $T/2<t<T$ $v_i=-V$

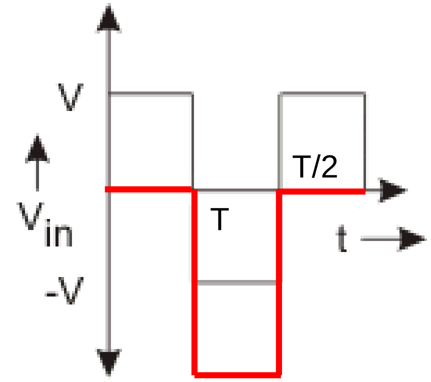
As the polarity of the voltage source changed in the negative half-cycle, the direction of current will also change and the diode will become reverse biased.



Now if we apply KVL, we get

$-V-V-v_o = 0$

i.e. $v_o = -2V$



As we can see, the signal waveform is only shifted by a dc value without being deformed.

For a clamper circuit to work properly:, we need that the capacitor charges quickly, i.e. the diode resistance is very small. Once the capacitor discharges through the load resistance it should discharge slowly as not to modify the input waveform significantly. That is R_LC should be very large in comparison to the period (T) of the input waveform.