# Basic Electronics
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## Lecture - 19
## Diode rectifiers

Welcome back to Basic Electronics. In this class, we will start looking at Diode Rectifiers. To start with, we will discuss the general functionality of rectifier and the meaning of the terms half-wave and full-wave rectifiers. We will then look at how addition of a capacitor filter changes the output waveforms.

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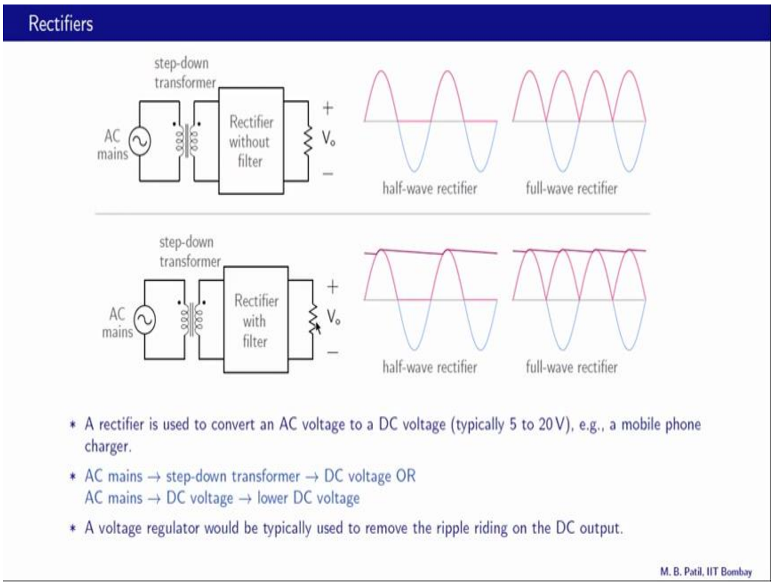

Rectifiers

- A rectifier is used to convert an AC voltage to a DC voltage (typically 5 to 20 V), e.g., a mobile phone charger.
- AC mains → step-down transformer → DC voltage OR
  AC mains → DC voltage → lower DC voltage
- A voltage regulator would be typically used to remove the ripple riding on the DC output.

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So, let us begin. We will now look at diode circuits for the purpose of rectification. A rectifier is used to convert an AC voltage to a DC voltage, which is typically in the range 5 to 20 volts; the AC voltage is generally the AC mains voltage 230 volts RMS, and a common example is a mobile phone charger. Now, in doing this, we have two possible approaches; one we start with the AC mains voltage, step in down to a lower AC voltage, and then convert it to DC that is one approach. In the second approach is we start with the AC mains and directly converted to a DC voltage, so this DC voltage would be a large DC voltage and then convert that large DC voltage to a smaller DC voltage using a DC-to-DC converter.

In this course, we will look at this first approach as illustrated in this schematic diagram here. We have the AC mains and that voltage is stepped down, with this step down transformer. After that we have the rectifier without filter. And we will very soon see what is the meaning of this filter here. And finally, we have the load, and here we have shown the load as a simple register, in real life it could be something else. And this voltage - output voltage is taken across the load. And our intention is to have V o as a DC voltage.

Let us now look at the waveforms. Here are the waveforms for half-wave rectifier without filter. This blue curve is the input voltage the step down input voltage as it appears over here; and the pink one is the output voltage V o. So, when V i is positive in this first half cycle V o is equal to V i; and when V i is negative V o is equal to 0. And it should be clear why this circuit is called a half-wave rectifier. In half of the period, the first half here V o is non-zero and in the second half V o is 0, so that is why half-wave rectifier.

Here are the waveforms for a full-wave rectifier without a filter. The blue waveform is the input voltage again as it appears here; and the pink waveform is the output voltage. And the difference between these two cases is obvious. In the full-wave rectifier case, if V i is positive, then V o is equal to V i and that part is similar to the half-wave rectifier case, but here when V i is negative the output voltage is not 0, but it is minus V i that means, it is positive. So, here the output voltage is on 0 and positive in both these half cycles and that is why it is called a full-wave rectifier.

Note that this waveform or this waveform is not what we are looking for; we are looking for a constant output voltage. So, therefore we are looking for a rectifier with filter never the less it is useful to look at these circuits rectifier without filter because that will make us understand this one better.

Let us look at the waveforms in this case, there is the input, there is the output of half-wave rectifier without filter and that is output the dark red curve of a half-wave rectifier with filter. So, it is almost a constant except for some small variation which we call as the ripple voltage and that is the situation for a full-wave rectifier with filter. So, that is the input that is the output, if we did not have a filter, and that is the output of a rectifier with filter. Again there is a small ripple voltage that we can see.

Now, typically a voltage regulator would be used after this stage, because we do not want this ripple voltage to be riding on our DC output. So, we would have AC mains then step down transformer then rectifier with filter then a voltage regulator and after that the load that is if we go for the first approach. And similarly we can also have the second approach implemented involving a voltage regulator.

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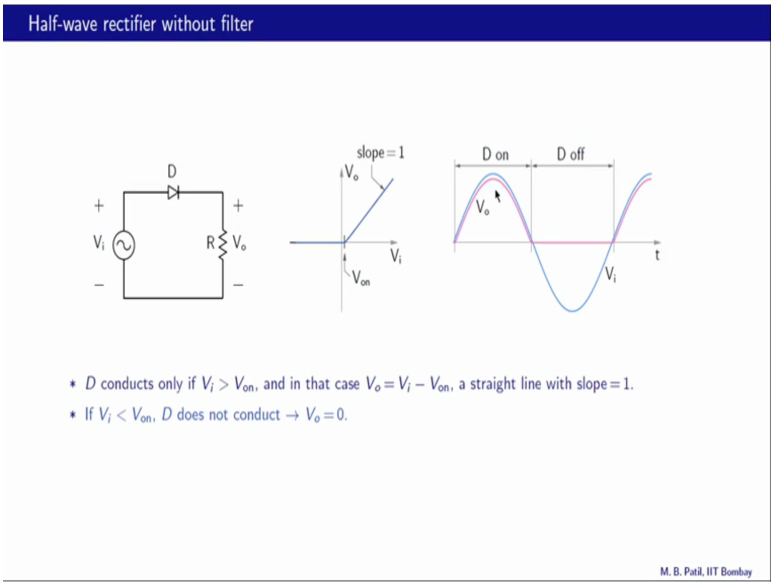
Half-wave rectifier without filter

- $D$ conducts only if $V_i > V_{on}$, and in that case $V_o = V_i - V_{on}$, a straight line with slope = 1.
- If $V_i < V_{on}$, $D$ does not conduct $\rightarrow$ $V_o = 0$.

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Here is a half favorite rectifier without a filter. Now, this AC source could be the AC mains or it could be a step down version of the AC main if we use a step down transformer. Now, the diode D conducts only if V i is greater than V on and in that case V o is V i minus the turn on voltage of the diode that is V i minus V on its a straight line with a slope equal to 1 that is shown over there. And if V i is less than V on then D does not conduct therefore, there is the voltage drop over there, output voltage is 0. Here is the time domain picture. The blue waveform is the input waveform, and the pink one is the output voltage waveform, D is on in this interval and it is often this interval. And when d is on these two are not exactly coinciding and that is because of this small v on voltage drop across the diode.

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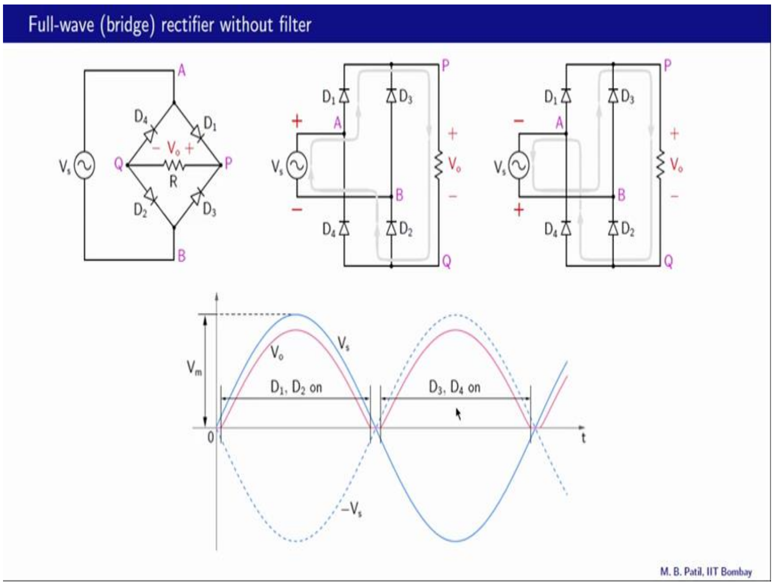

Full-wave (bridge) rectifier without filter

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Here is a full-wave rectifier without a filter and it is also called a bridge rectifier because we have this diode bridge here. The AC source V s is connected between nodes A and B, and the load the register here R is connected between nodes P and Q. Now, let us look at the current path when V s is positive and when V s is negative. When V s is positive node A is at a higher potential than node B and the current flows from the source through D 1 through R then through D 2 and then back. When V s is negative node B is at a higher potential than node A and then the current flows from the source through D 3 through R through D 4 and then back. Now, the important thing to notice is in both these cases that is with V s positive and with V s negative, the direction of the current through R is like that the same in both cases. And therefore, V o is always positive and that is why this is a full-wave rectifier.

Let us redraw the circuit in a more friendly format which is easier to look at as shown over here. And let us make sure that these two circuits are actually the same. The source is between nodes A and B here and it is also between nodes A and B here. The load is between P and Q and that is true here as well. D 1 is between A and P, A and P; D 2 between Q and B, Q and B; D 3 between B and P, between B and P here; and D 4 is between Q and A and the same thing here between Q and A. So, these two circuits are identical and let us now use this circuit for our further analysis.

Let us consider V s to be positive then node A is at a higher potential than node B, and the conduction takes place through D 1 then the load resistor and then through D 2. Now, if there is no voltage drop across D 1, so let us say V on is 0 for D 1 and also for D 2, then node P is at the same potential as node A and node Q is at the same potential as node B. In other words, the output voltage V o is then equal to the input voltage V s. In reality of course, there would be some voltage drops across D 1 and D 2, V on equal to say 0.7, and then the output voltage would differ slightly from the input voltage.

Let us consider the other case now V s negative. Now, node B is at a higher voltage compute to node A, and the conduction path is through D 3, then through the load resistor and through D 4. And in both of these cases node that the current is downward here as well as here and therefore, V o is always positive and that is why it is a rectifier. Once again taking the simple case where the on voltage of the diodes is 0, this node P is now at the same potential as node B; and node Q is at the same potential as node A. In other words, V o is now equal to minus V s. And in reality of course, there will be a slight difference because of the V on of the diodes.

Let us look at the waveforms now. The blue curve is the input voltage V s and that goes from plus V m to minus V m. The dash curve is minus V s. In the first half cycle, when V s is positive, we have seen the D 1 and D 2 conduct; and in that case V o is nearly equal to V s and that is what we observe over here. And difference between these two is the V on drops across the diodes. In this half cycle, V s is negative and minus V s is positive; in this case D 3 and D 4 conduct. And as we have seen V o and minus V s are nearly equal and that is what we see over here that is V o that is minus V s, and they are nearly equal the difference of course, is because of the V on drops across D 3 and D 4.

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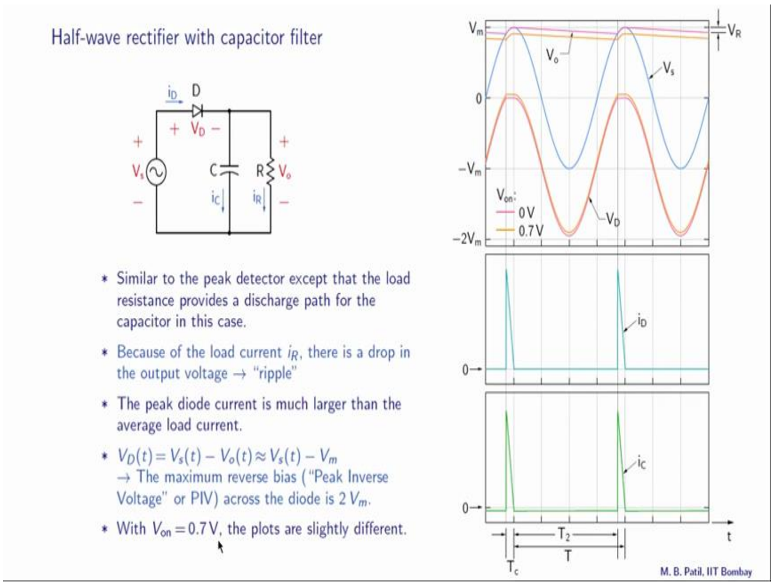

## Half-wave rectifier with capacitor filter

- Similar to the peak detector except that the load resistance provides a discharge path for the capacitor in this case.
- Because of the load current $i_R$, there is a drop in the output voltage → "ripple"
- The peak diode current is much larger than the average load current.
- $V_D(t) = V_s(t) - V_o(t) \approx V_s(t) - V_m$
  → The maximum reverse bias ("Peak Inverse Voltage" or PIV) across the diode is $2\,V_m$.
- With $V_{on} = 0.7\,V$, the plots are slightly different.

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Let us now look at the half-wave rectifier with a capacitor filter. And it is similar to the half-wave rectifier circuit we have seen before except for the capacitor. In the half-wave rectifier, we had the diode and load resistor; and now we have this capacitor added in parallel with the load resistor. Now, this circuit is very similar to the peak detector circuit that we saw earlier in which we had the diode and the capacitor, but not this load resistor. And as a result what happened is this output voltage tracked the peak of the input voltage. Now, this circuit is not quite the same, but it is very similar. The difference is that in this case we have a load resistor, which is going to draw current. And therefore, that current will provide a discharge path for the capacitor.

In the case of the peak detector, this was not there and there therefore, there was no path for the capacitor to discharge because the diode cannot conduct current in the reverse direction. Perhaps the easiest way of looking at the half-wave rectifier circuit with capacitor filter is to imagine that this resistance is infinite. And if that is the case then the circuit is the same as the peak detector circuit, and then what is going to happen the output voltage is then going to be equal to the peak of the input voltage and what is the peak of V s, V s varies from minus V m to plus V m. So, the output voltage is going to be plus V m and that will be held constant. Of course, there will be this V on voltage drop across the diode, but if V on is negligible compared to other voltages then we can say that the output voltage is constant.

And now let us look at what happens in the presence of a finite load resistor that is when the load resistor starts drawing a current. These are the waveforms. This is the input voltage V s that is the output voltage V o that is the voltage across the diode, that is the diode current, and that is the capacitor current. First we note that the diode conducts only in a very short interval compared to the period of the waveform and that corresponds to this part of V o. And when the diode is not conducting, we have only this circuit; by this time the capacitor has already charged to V m and now the diodes have stopped conducting.

So, what happens is the capacitor starts discharging through this resistor, and that is why we see a drop in V o. At this point the input voltage rises again about the output voltage that is the p end of the diode is now higher than the n end of the diode and the capacitor gets charged again. And this process is instantaneous because the time constant for this charging is very, very small. Why it is small, let us look at the circuit from the capacitor what we see is this resistance and the diode resistance in parallel and that is of course, nearly equal to the R on off the diode, which is very, very tiny.

Because the resistance seen by the capacitor is very small, the time constant for the charging process is very small, and as a result the output voltage follows the input voltage instantaneously and that is what we see over here, and that goes on up to this point and now the input voltage starts decreasing. So, the voltage at the p end of the diode is now going down, this voltage has not really changed, and therefore, the diode stops conducting. And now this part is isolated from the rest of the circuit. So, we have this R c circuit, the capacitor now discharges through the resistor and that are what we see over here once again. And this process goes on. And because of this we see a small variation in the output voltage, it is not quite V m, here it is close; but there is a small voltage drop in V o.

So, because of the load current i R - this current, there is a drop in the output voltage and that drop is called the ripple and its denoted by V R, R standing for ripple voltage. Let us also look at the currents as we have already remarked earlier, the diode current is nonzero only in this small interval, when the capacitor is charging, then the diode turns off, so zero current. And then again the charging interval comes and the diode current becomes nonzero. Now, it turns out that the diode current here is very large compared to the average i R, and do we see that average i R anywhere in this figure that is right here.

This figure shows the capacitor current; and in this interval, the diode is not conducting and therefore, i C and i R are the same of course, with the negative sign. So, i C then is minus i R. And you can see that this is over 0 here and the i C value which is the same as i R in magnitude is very small as compared to the diode current here. These are drawn of course, on the same scale although this scale is not shown, so that is another very important observation to make that is the peak diode current is much larger than the average load current.

The peak diode current turns out to be much larger than the average load current. What is the meaning of this, the peak diode current means the maximum instantaneous current that flows through the diode, and that turns out to be much larger than the average value of this register current that is i R. Now, why is this peak diode current important that is because when diodes are fabricated this diode has a certain maximum current limit for example, some diode may be able to conduct only up to 10 milliamps, some other diode might be able to conduct up to 10 amperes and so on. So, when we design a circuit like this, we must know beforehand what is the maximum current that is going to flow through this diode and therefore, we can choose a diode which has a maximum current rating higher than that particular value.

Next, let us look at V D the diode voltage. What is that given by K v l we can say that V s must be equal to V D plus v o. So, therefore, V d is V s minus V o as given by this equation here. What about V s of t that is V m sine omega t or V m cos omega t depending on where we take the origin. What about V o of t, V o of t is nearly constant provided this ripple voltage is small, and that is indeed the case in practice. So, therefore, we can say that V o is nearly equal to V m.

We are interested in finding the maximum magnitude of V D of t. Now, we know that V s of t varies between minus V m and plus V m; when V s is plus V m V D is zero V m minus V m; and when V s is minus V m V D is equal to minus V m minus V m that is minus 2 V m. So, therefore, we expect V D to vary between minus two V m and 0 and that is indeed observed in this plot here. This is our V D the maximum value is 0 volts and that happens when the diode conducts and the minimum value is minus 2 V m.

And when V D is minus 2 V m the diode is; obviously, under reverse bias. Now, we might ask this question why is this V D important, why do we worry about it and the answer has to do with something called the peak inverse voltage or PIV rating of the diode; this rating specifies the maximum reverse bias that the diode can withstand. As an example let us say V m is 10 volts in that case the maximum reverse bias that the diode will come across is 2 V m at that point and that would be 2 times 10 or 20 volts. And therefore, we must pick a diode with a PIV rating more than 20 volts.

Finally, let us take a look at the results when V on is not 0, but 0.7 volts. And the plots are slightly different. Here we have plotted V o - the yellow line there, and V D, when V on is 0.7 volts. Now, as we see the maximum value of V o is not V m anymore, but it is V m minus 0.7 and that is because we have this diode voltage drop here. So, this node does not really reach V m, but V m minus 0.7. Apart from that we do not really see a big difference between the earlier V o and this V o the ripple voltage also remains approximately the same. And also the diode voltage is nearly the same as before. We have not shown i D and i C when V on its 0.7 volts, but this circuit file is available and we can run this simulation, and verify that the results are not really too different.

To summarize, we have looked at the meaning of the terms half-waves and full-wave rectification we have seen an implementation of a half-wave rectifier with and without a filter; and observed the associated waveforms. We will continue this discussion in the next class, until then goodbye.