# Basic Electronics
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## Lecture – 48
## Precision rectifiers (continued)

Welcome back to Basic Electronics. In this lecture, we will look at a precision half-wave rectifier in which the op-amp does not enter the saturation region. We will then see how a precision full wave rectifier circuit can be made up using the circuit blocks we have already seen. Finally, we will look at wave shaping using diodes, and how to use it to convert a triangular input voltage to sinusoidal output voltage. Let us get started.

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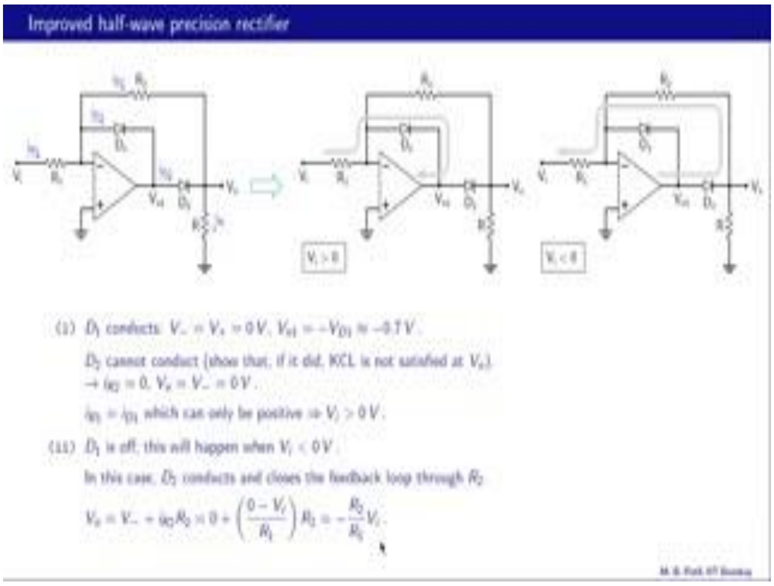

Improved half-wave precision rectifier

(i) $D_1$ conducts: $V_- = V_+ = 0\,V$, $V_{o1} = -V_{D1} \approx -0.7\,V$.

$D_2$ cannot conduct (show that, if it did, KCL is not satisfied at $V_o$).
$\rightarrow i_{R2} = 0$, $V_o = V_- = 0\,V$.

$i_{R1} = i_{D1}$ which can only be positive $\Rightarrow V_i > 0\,V$.

(ii) $D_1$ is off; this will happen when $V_i < 0\,V$.

In this case, $D_2$ conducts and closes the feedback loop through $R_2$.

$$V_o = V_- + i_{R2} R_2 = 0 + \left(\frac{0 - V_i}{R_1}\right) R_2 = -\frac{R_2}{R_1} V_i .$$

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Let us now look at an improved half-wave precision rectifier. And what is the improvement we are seeking over the super diode circuit, the improvement we are looking for is that the op-amp should not enter saturation, because as we have seen that affects the speed of the circuit. Let us see how this circuit works. There are two diodes now D 1 and D 2. So, we will take two cases case one in which D 1 conducts; and case two in which D 2 conducts. Case one - D 1 is on this loop is then complete and then the op-amp operates in the linear region, therefore V minus and V plus are equal; V minus is 0 volts. What about V o 1 in that case, V o 1 is V minus minus this voltage drop, so that is 0 minus about 0.7, so V o 1 is therefore minus 0.7 volts.

Now, if that happens we can show that D 2 cannot conduct, so that if it did than case l is not satisfied at this node. Let us do that suppose D 2 did conduct, what would be this voltage this is 0 volts, 0 minus 0.7 minus 0.7, so this V o would be minus 1.4 volts. This is 0, this is minus 1.4, so this R 2 would conduct like that, and this R would also conduct a current going into that node, because this is 0 and this is minus 1.4 volts. So, this current is going in also this current is also going in. So, the only way KCL can be satisfied is for D 2 to conduct in that direction and that cannot happen because that would be the reverse direction for D 2.

So therefore, we conclude that D 2 cannot conduct in this situation. If D 2 does not conduct then we have an open circuit here and then R 2 and R are in series. This end is at 0 volts and this end is also at 0 volts, so obviously, we cannot have any current in this path. So, this voltage drop as well as this voltage drop is then 0, and V o is equal to 0. So, our situation now is D 1 conducts D 2 does not conduct i R 2 is 0, i R is also 0.

Let us now see what values of V i this situation corresponds to. So, this is our current path like that. And V minus is 0 volts, and the only way this can happen is if V i is positive. So, the situation that we have discussed D 1 on, D 2 off can happen only if V i is positive. Clearly, if V i is negative then we cannot have D 1 conducting and that brings us to the second situation namely D 1 is off. And let us look at this situation in more detail now.

In this case, the conduction path is like this, diode D 2 conducts and that is how the current flows. The loop around the op-amp does flows and therefore, the op-amp operates in the linear region V minus and V plus are equal, V minus is therefore 0. And because the current is flowing at that direction V i is negative. So, this is a consistent picture. Let us now figure out, what V o should be in this case that is easy to do. What is V o it is equal to V minus plus this voltage drop V minus is 0. And for this voltage drop, we need that current that current is the same as this current, and this current is 0 minus V i divided by R 1 like that. And after putting it all together, we get V o equal to minus R 2 by R 1 times V i. So, we have two situations D 1 conducting V o equal to 0; and in that situation D 2 does not conduct; D 2 conducting V o equal to minus R 2 by R 1 times V i and in that situation D 1 does not conduct.

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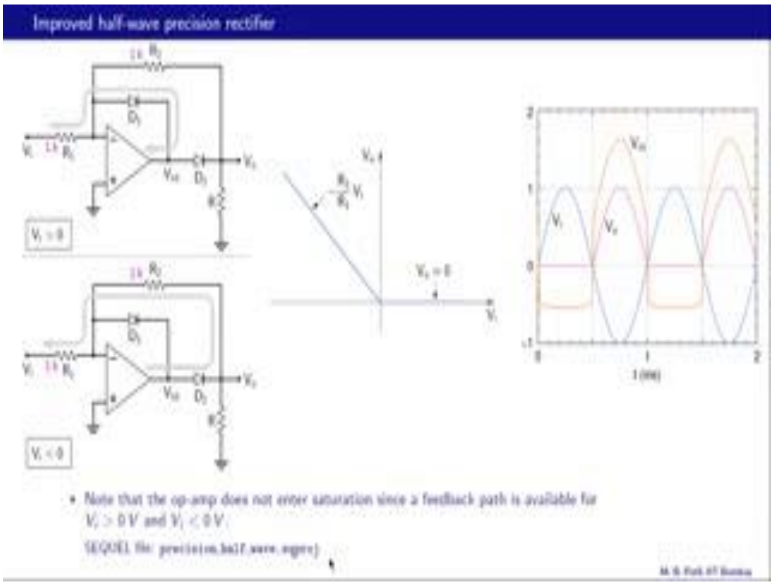

Improved half-wave precision rectifier

- Note that the op-amp does not enter saturation since a feedback path is available for $V_i > 0\,V$ and $V_i < 0\,V$.

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Here is the summary of the improved half-wave precision rectifier. Positive V i - D 1 conducts D 2 does not conduct V o is 0 as shown here. Negative V i - D 2 conducts D 1 does not conduct and V o is minus R 2 by R 1 times V i, so that is a straight line with a negative slope and going through the origin and that is what the waveforms would look like. When V i is positive, the output voltage is 0; and V i is negative, the output voltage is positive. And in this example, we have taken R 2 and R 1 to be equal. So, therefore, V o and V i are equal in the magnitude.

What is the big advantage of this circuit over the super diode circuit, the op-amp always operates in the linear region it does not enter saturation and that is very clear. If we plot this voltage V o 1, and that looks like this and clearly it does not go to plus minus V sat. Let us see if we can work out, what V o should be in each of these regions. When V i is positive, V 1 conducts this is virtual ground. So, therefore, V o 1 would be minus V r, so that is what we observe over here. This is not quite minus 0.7 the exact value would really depend on the current levels. What about V i negative we have this situation now and then V o 1 is V o plus V 1 of D 2 and that is what we observe over here. And in the other case the op-amp does not enter saturation, since the feedback path is always available. Here is a circuit file for this simulation.

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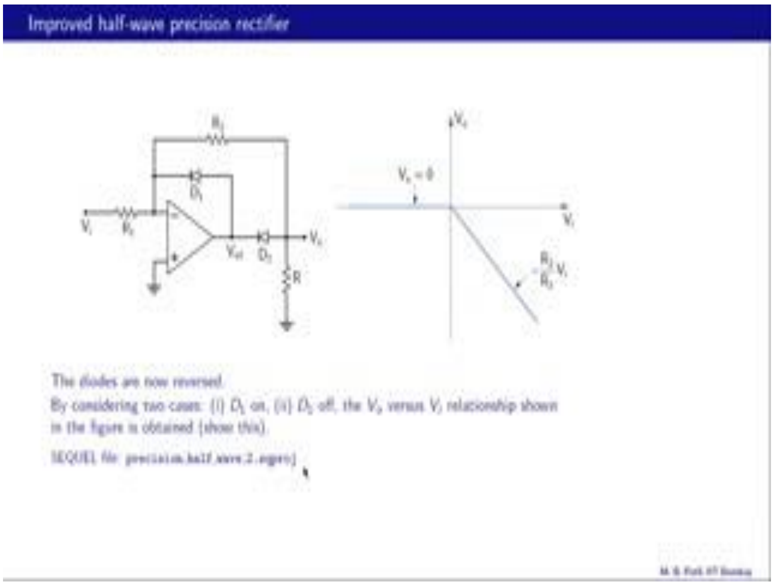

Improved half-wave precision rectifier

The diodes are now reversed.

By considering two cases: (i) $D_1$ on, (ii) $D_1$ off, the $V_o$ versus $V_i$ relationship shown in the figure is obtained (show this).

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Here is another improved half-wave precision rectifier; looks very similar to the circuit we just discussed except the diodes are now reversed. And as a result, we obtain this V o versus V i relationship shown on this figure here. So, take this as homework, figure out the conduction paths when D 1 is on and D 1 is off, and obtain this V o versus V i relationship. The circuit file is also available; you can try out the simulation as well.

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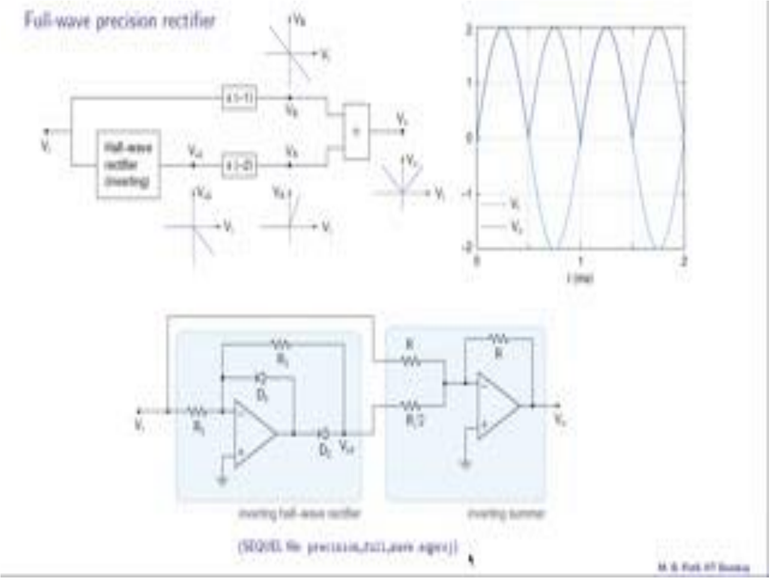

Full-wave precision rectifier

inverting half-wave rectifier

inverting summer

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We can use the circuits, we have already looked at to makeup full-wave precision rectifier. And here is a block diagram V i is the input voltage, V o is the output voltage and the relationship between V o and V i that we would like is shown here. This is a half-wave rectifier inverting it gets V i as the input, its output is V o 1; and the relationship between V o 1 and V i is shown here. When V i is negative, V o 1 is 0; and when V i is positive, V o 1 is minus V i. V o 1 is multiplied by minus 2 to obtain V a. Now, in this region when V i is negative multiplying by minus 2 does not make a difference, so V a is also 0 here. In this region when V i is positive V o 1 is minus V i and multiplying that by minus 2 will give us plus 2 times V i and that is what is shown over here.

Now, this plot here multiplies V i by minus 1 to give V b. So, if we plot V b as a function of V i, we get a straight line passing through the origin with a slope of minus 1. And now what we do is add V b and V a and obtain our final output voltage. Now, when V i is negative, V a is 0. So, this part goes through as it is right there. When V i is positive, we have a slope of minus one here and the slope of plus 2 here. So, the net slope is plus 1 and that is how we obtain our desired V o versus V i relationship. Let us now see how this can be implemented with circuits.

Here is a circuit implementation of the block diagram. This block is the inverting half-wave rectifier and we have selected these two resistances to be equal, so as to get a slope of minus 1 here. So, this block uses V o 1 versus V i given by this graph, so that is V o 1. Now, this other three functions this multiplication by minus 2 multiplication by minus 1 and addition, these three functions are performed by this single block the inverting summer that we have already seen earlier.

What does it do let us look at the resistances this is R, this is R, and this is R by 2. So, V o is equal to minus V i minus 2 times V o 1, and that is exactly what we want. V o is minus V i minus 2 times V o 1 in the block diagram as well. So, this circuit will perform full-wave precision rectification. Here is the simulation result that is our input voltage - the light blue curve and that is the output voltage. And here is the circuit file.

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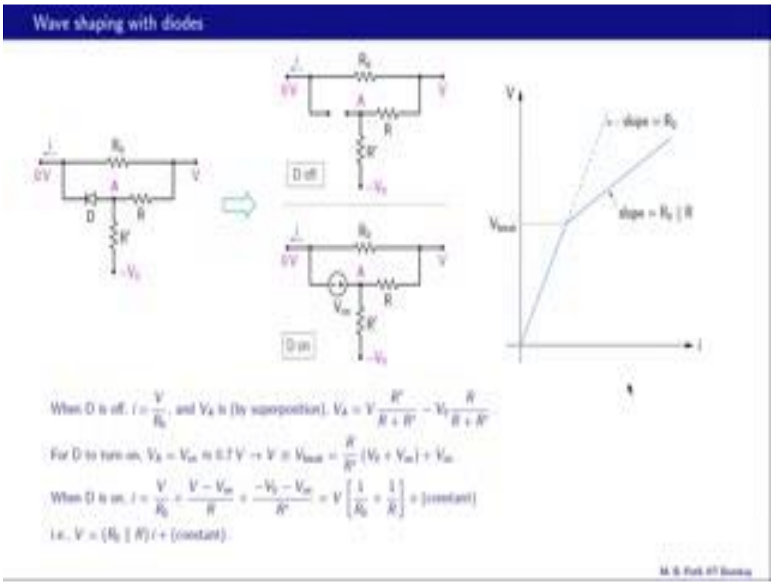

Wave shaping with diodes

When D is off, $I = \frac{V}{R_0}$, and $V_A$ is (by superposition), $V_A = V\frac{R'}{R+R'} - V_0\frac{R}{R+R'}$.

For D to turn on, $V_A = V_{on} \approx 0.7\,V \rightarrow V \equiv V_{break} = \frac{R}{R'}(V_0 + V_{on}) + V_{on}$.

When D is on, $I = \frac{V}{R_0} + \frac{V - V_{on}}{R} + \frac{-V_0 - V_{on}}{R'} = V\left[\frac{1}{R_0} + \frac{1}{R}\right] + (\text{constant})$

i.e., $V = (R_0 \parallel R)\,I + (\text{constant})$.

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Let us now talk about wave shaping with diodes. What is the meaning of wave shaping? Let say we have an input triangular wave and we want to convert that into an output sinusoidal wave that is an example of wave shaping. Here is a simple diode circuit and we will see that this can be used for wave shaping. We will take this node voltage as 0 volts, and there is a good reason for doing that as we will see later. This node is sitting at minus V 0 a constant voltage, it could be minus 5 volts or minus 10 volts for example, that is the power supply. And what we want to do is to plot this V as a function of this current I here.

First, let us consider D to be off not conducting, so this is an open circuit. And when D is off, what is the current it is simply V minus 0 divided by R 0, so V by R 0. And what is this node voltage with respect to ground, we have V here, we have minus V 0 here, and this is an open circuit. So, we can obtain V A by super position and that is given here V A is V times R prime by R prime minus V 0 times R by R plus R prime, so that is our V A when a diode is not conducting.

Let us look at this equation. And let us say V is positive. Now, this term is positive if V is positive and this term is negative. As V increases V A will also increase and at some point it will reach 0.7 volts. Now, V A becoming 0.7 volts means the diode turns on and that provides a break point in the V versus I relationship. So, for D to turn on V A should be V on which is about 0.7 volts, and that gives us this break point. So, what do we do we put V A equal to V on here and solve for V break. So, V break then turns out to be R by R prime time V o plus V on, this is a positive number remember because minus V 0 is negative that plus V on, so that is our V break. So, when this voltage here is equal to V break, the diode starts conducting, and then we have this equivalent circuit. So, the diode is now replaced with this battery here let say 0.7 volts.

Let us now look at this current when the diode is conducting; it is composed of two parts, this current and that current. Now, this first part is the same as before V minus 0 divided by R 0 that is V by R 0. And this second current, we can find by adding this current and this current. Now, when the diode is conducting, since this is 0 volts, this V A is equal to V on. What is this current then it is V minus V on divided by R that is this second term here. And what is this current, it is minus V 0 minus V on divided by R prime, the third term here. Now, we can combine terms containing V that is V times 1 over R 0 plus V times 1 over R like that. And all the other terms are essentially constants because V on is a constant V o is a constant.

So, we can write our current as V times this 1 over R 0 plus 1 over R plus some constant. In other words, if you want to write V in terms of I that will look like this, this R 0 parallel R comes from this term. And now we have all the information we need to plot V as a function of I, and that is a plot. So, let us try to understand this plot. So, when V is small in this range, the diode is off; and the only current is the current through this R 0, and therefore, the slope of this part is R 0. At this point, when V is V break the diode turns on; and now the slope of V versus I is R 0 parallel R, which is of course, smaller than R 0, so that gives us this segment here. So, that is a overall V versus I relationship for this circuit.

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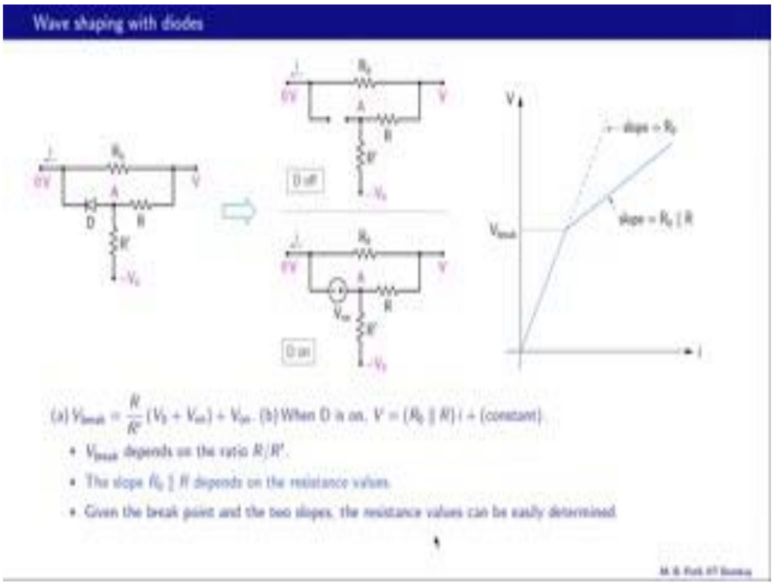

Wave shaping with diodes

(a) $V_{break} = \frac{R}{R'}(V_0 + V_{on}) + V_{on}$. (b) When D is on, $V = (R_0 \parallel R)\, i + (\text{constant})$.

- $V_{break}$ depends on the ratio $R/R'$.
- The slope $R_0 \parallel R$ depends on the resistance values.
- Given the break point and the two slopes, the resistance values can be easily determined.

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In summary, we have V break equal to R by R prime time V 0 plus V on plus V on that is a break on there. And when the diode is conducting, V is given by R 0 parallel times i plus the constant. So, if you look at this V versus i relationship, we notice that there are three design parameters; one - the slope of this part which is given by R 0; second - the slope of this part which is given by R 0 parallel R; and third - this break part which is given by this expression here. And note that V break depends only on the ratio R by R prime and not on the actual values of R and R prime.

Whereas, the slope R 0 parallel R does depend on the actual resistance values. And therefore, given the break point and the two slopes, the resistance values can be easily determined and that is why this circuit is very attractive.

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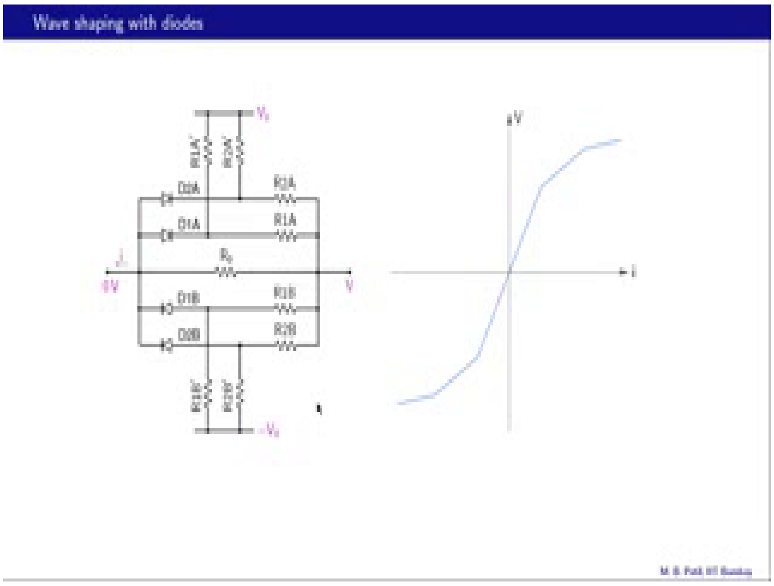

Wave shaping with diodes

So, what have we got so far, we have this V versus R relationship and we have seen that this break point is provided by this diode, when the diode starts conducting we have the break point. And this slope here is R 0 parallel with R 1 B here. Now, what we will do is to introduce another branch just like this first one with different resistance values and that is what it looks like. What will this branch do, this will introduce one more break point in the V versus i relationship. And we can design the resistance values such that this break point the second break point occurs after the first break point. And what is this slope this slope is R 0 parallel with R 1 B parallel R 2 B.

We can now add a complimentary branch like that. Note that the diode polarity is now different than this one. Also this voltage here is positive, not negative. And with this branch we can add a break point in this part now of the V versus i relationship and that is what it looks like. And you can work out the expression for the break point in this case and also what happens to this slope here and so on. And if you add one more branch like the first one like that then we have one more break point like that. So, this is the net V versus i relationship that we can obtain with this network. And we will see how we can use this entire network for wave shaping.

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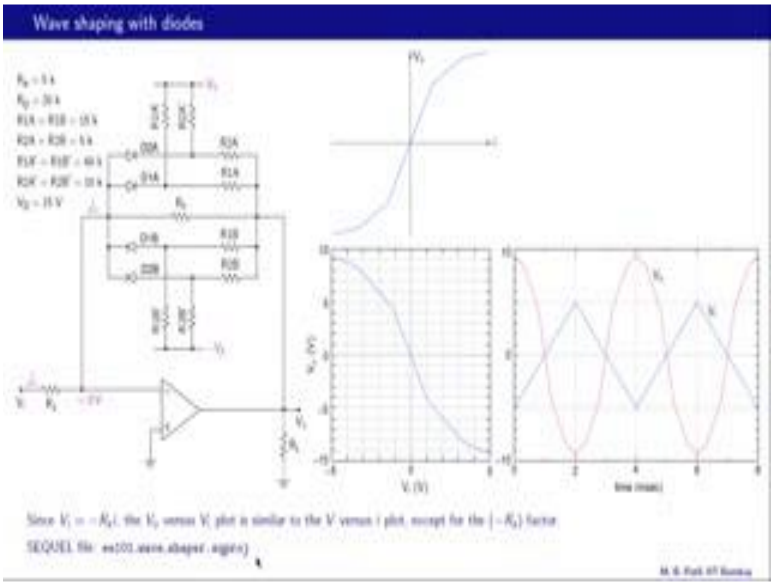

Wave shaping with diodes

What we have done now is to place this entire diode network, which we saw in the last slide in the feedback path of this circuit. Now, notice that this circuit would otherwise be an inverting amplifier. And what we have done is to replace R 2 of that inverting amplifier by this network here. And now it should be image should be clear, why we took this voltage here as 0 volts, because V minus and V plus are equal, this node is at virtual ground, and therefore it makes sense to treat that as 0 volts. And as we have seen before the relationship between this voltage and the current is given by that curve. And what is this voltage in this circuit; it is a same as V o. So, now, we know the relationship between V o and i.

Our next job is to relate this i to input voltage V i and that is easy to do because this i is the same as this current. And since this is at 0 volts, this V i is simply 0 minus this voltage drops or minus R a times i. In other words, V i is simply a scaled version of i and this scaling factor is given by minus R A. So, using this fact, we can map this V o versus i relationship to the V o versus V i relationship and that is what is shown over here and of course, it has got reflected around the y-axis because of this minus sign.

So, now if we apply an input voltage, which is triangular in shape that is what we get as the output voltage. And as you can see, it is close to a sinusoid. And in the next slide, we will see how good it is how close it is to a sinusoid. Here is the sequel circuit file, you can run this simulation and check out these results.

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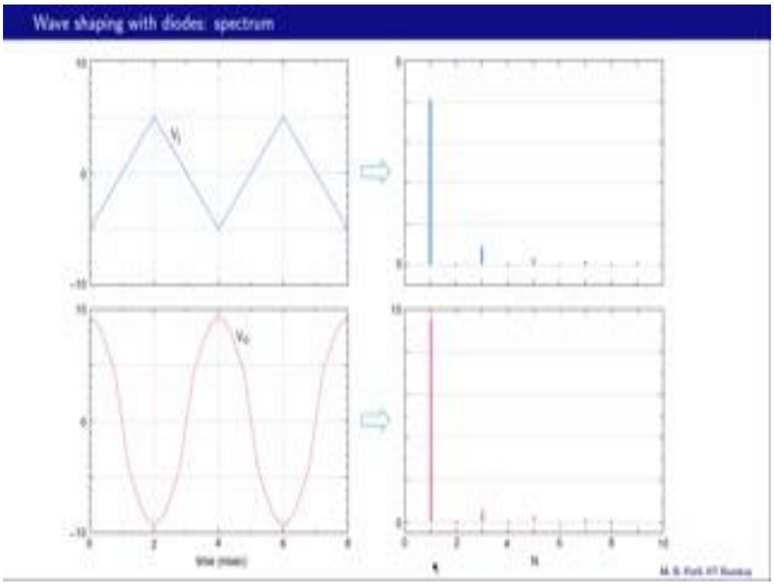

Wave shaping with diodes: spectrum

We will now look at the spectrum of V i as well as V o to figure out whether our output voltage is close to a sinusoid or not. Let us start with the input voltage first; here is the spectrum this is the fundamental frequency, let us say f this is 2 f, 3 f and so on. And for a pure sinusoid, we would expect this to be nonzero, but all others to be 0 and obviously, this is not a sinusoid and therefore, we have nonzero components at this other frequencies. This even harmonics have got eliminated because of symmetry. So, what is a measure of closeness to a sinusoid, we want these harmonics to be small. So, in other words, this amplitude should be as small as possible as compared to this amplitude.

This is our output voltage, and of course visually we can definitely say that it is closer to a sinusoid than the input triangular waveform, but we want to look at the spectrum now and see that more quantitatively. So, here is a spectrum, and it should be clear when we compare these two figures that the relative magnitude of the third harmonic as compared to the fundamental has done down for sure and that indicates that our output voltage is closer to the sinusoid than the input voltage.

To summarize, we have seen precision half-wave and full-wave rectifier circuits, in which the op-amp works only in the linear region. Since, the op-amp is not allowed to enter the saturation region, these circuits are relatively fast. We have also seen how diodes can be used for wave shaping; and in particular, for converting a triangular input to a sinusoidal output. In the next class, we will simulate the triangle to sign converter circuit. So, see you next time.