Basic Electronics
Prof. Mahesh Patil
Department of Electrical Engineering
Indian Institute of Technology, Bombay

Lecture – 52
Schmitt Triggers (continued)

Welcome back to Basic Electronics. In this lecture, we will continue with Schmitt triggers. We will look at a Schmitt trigger circuit which allows the threshold voltages V TH and V TL to be shifted using a reference voltage. We will then start with a new topic namely sinusoidal oscillators. First, we will discuss the principle behind these circuits and then look at some specific examples. Let us start.

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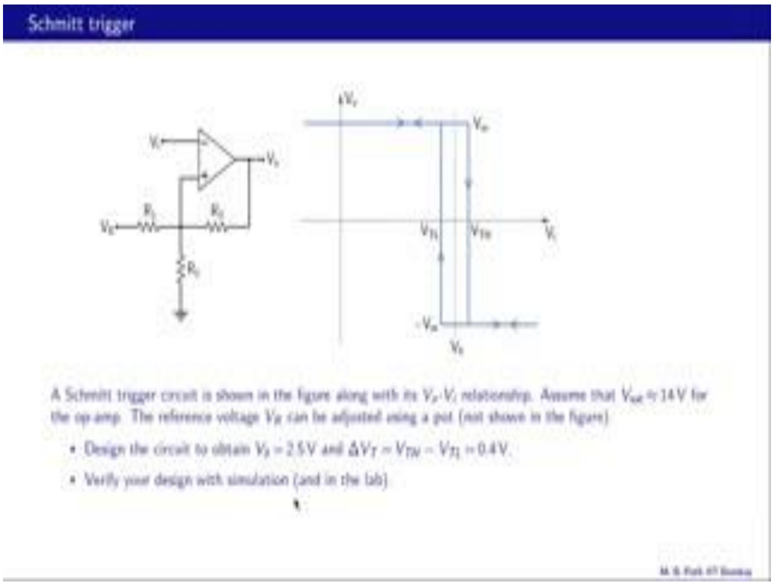

Let us look at this modified Schmitt trigger circuit with the V o versus V i relationship shown here. Essentially, it is an inverting Schmitt trigger, but here the V TL and V TH are not symmetrically placed around V i equal to 0. They have been shifted along the V i axis. And this shift depends on this reference voltage as we will find out. This reference voltage can be adjusted using a part, which we have not shown in the figure. And our task is first of all to understand how the circuit works, and then we want to design it to obtain V 0 equal to 2.5 volts, where V 0 is this voltage here at the center of this interval between V TL and V TH, so that is one design specification given to us. The other specification is delta V T, which is the difference between V TH and V TL; this difference should be equal to 0.4 volts.

And once we design the circuit then we will simulate it and make sure that it works as we designed it. And you can also go to your electronics lab setup the circuit and verify its operation.

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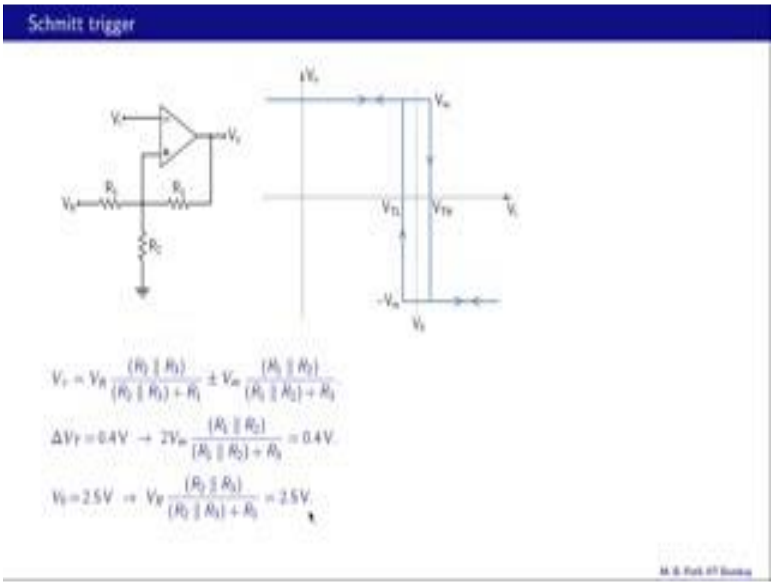

Let us now try to understand how the circuit works. Let us say we are somewhere here on the V o versus V i curve that means, our V o is plus V m and V i is let us say 0 volts. And now we are increasing V i; and at V i equal to V TH the output is going to flip from plus V m to minus V m. So, the key point is this V plus when our V i which is equal to V minus crosses V plus that is when this output is going to change from V m to minus V m.

So, let us find what that V plus is in that situation. So, we have V o equal to plus V m which is 14 volts V R is a constant dc voltage, for example, 2 volts and this current is 0 because there is the input current for the op-amp. And in this situation, we can use superposition to find V plus. We have two voltage sources V R and V m. We can take them one at a time, find V plus in each case and then add the two V plus values. Let us consider V R first with this voltage equal to 0 that means, this node is at ground potential and then R 2 and R 3 R n parallel. And in that case V plus can be obtained simply using voltage division and V plus would be V R times this resistance which is R 2 parallel R 3 divided by R 1 plus R 2 parallel R 3 that is the first term here.

Next we consider this voltage that is V m and take V R as 0. Now, what happens is R 1 and R 2 come in parallel, and V plus once again using voltage division is given by V m the potential here times R 1 parallel R 2 divided by R 3 plus R 1 parallel R 2 and that is the second term over here with the plus sign. So, that is V plus when V o is equals to plus V m and that essentially gives us V TH. Similarly when we are here V o is minus V m and now V plus is the same expression with a minus sign here and that gives us V TL. And now let us look at the specs that we have been given. Delta V t which is the difference between V TH and V TL has been specified as 0.4 volts and when we subtract V TL from V TH this term drops out, and we get two times V m times this voltage division vector, so that should be equal to 0.4 volts, and that is our first condition.

The second specification is that V 0 should be equal to 2.5 volts. What is V 0, it is nothing but V TL plus V TH divided by 2. And when we add V TL and V TH, the second term drops out, because in V TL we have a minus sign here and in V TH we have a plus sign here. So, what we get then is V R times R 2 parallel R 3 divided by R 2 parallel R 3 plus R 1 equal to 2.5 volts. So, let us now use these two conditions to design our circuit.

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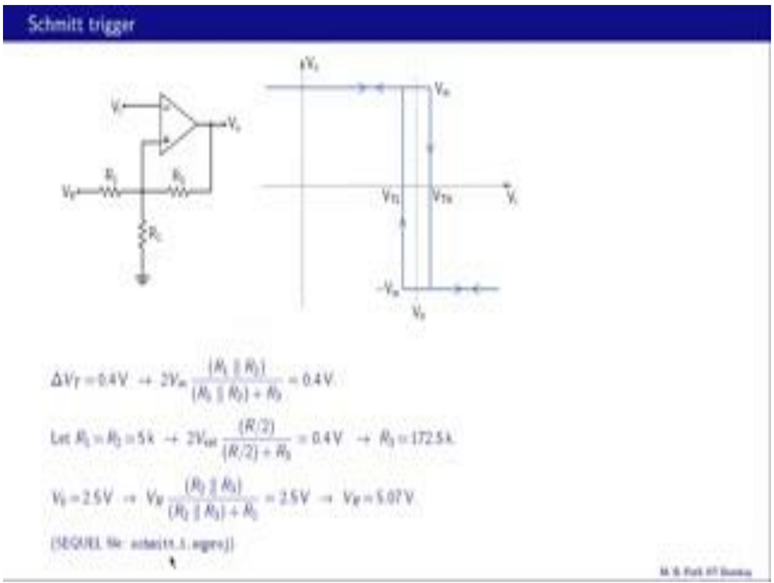

For delta V T to be 0.4 volts, we want this quantity to be 0.4; V m is already known that is the same as V sat for the op-amp given to be 14 volts. So, we should now select suitable resistance values, so that this fraction multiplied by 2 V sat gives us 0.4. Let us make a choice here, let R 1 and R 2 be equal, and let us call that R, and let that be 5 k. In that case, this quantity can be replaced with 2 times V sat R 1 parallel R 2 becomes R parallel R that is R by 2. So, R by 2 in the numerator, R by 2 plus R 3 in the denominator, and R is already known we have selected that to be 5 k. So, this equation can now be solved for R 3; and R 3 turns out to be 172.5 k.

Our other constraint is V 0 equal to 2.5 volts that implies that V R times R 2 parallel R 3 divided by R 2 parallel R 3 plus R 1 should be 2.5 volts. Now, the resistance values are already known R 3 is 172.5 k, R 1, R 2, R equal 5 k each. So, this number can be calculated and that gives us V R equal to 5.07 volts. So, this reference voltage should be 5.07 volts; in practice of course, it is going to be adjusted using a part. Now, we are going to simulate this circuit and in fact the circuit file is available to you, you can also run this simulation if you like. And let us now conform with the simulation results that our design is correct.

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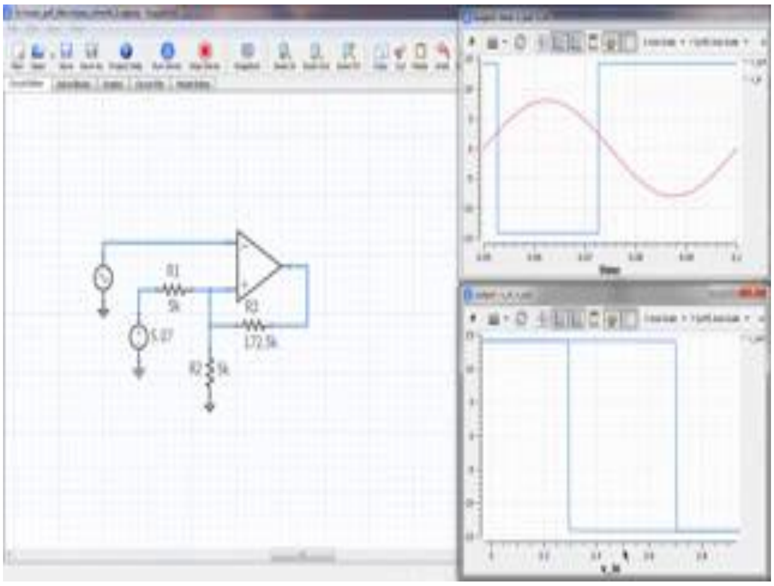

Here is the circuit schematic. We have R 1 equal to R 2 equal to 5 k, R 3 is 172.5 k, and V R the reference voltage is 5.07 volts. As input we have applied a sinusoidal voltage here, and let us now look at the results. So, this is the input voltage and that is the output voltage. So, the output voltage is plus 14 volts here that is plus V sat then it changes to minus 14 that is minus V sat and then back to plus V sat. This is the V o versus V i plot this is our V TL that is 2.3 volts, this is our V TH 2.7 volts. And we now need to check two things - one delta V t that is the difference between V TH and V TL should be 0.4 volts, this is 2.7, this is 2.3, so the difference is into 0.4 volts. Second - the center of this interval which we have called as V 0 should be 2.5 volts and that is also observed over here.

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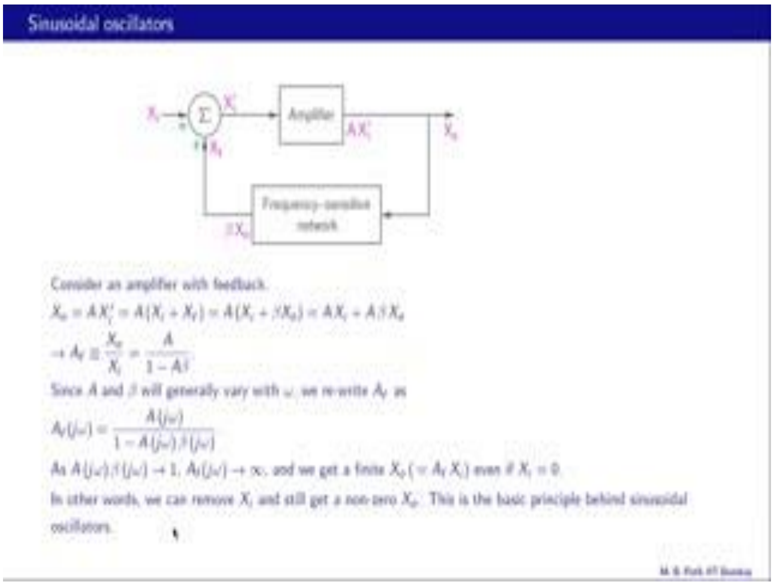

So, that shows that our design is correct. We will now look at sinusoidal oscillators which produce sinusoidal output voltages, and we begin with an amplifier with feedback as shown in this picture. Here is an amplifier, its input is X i prime its gain is A. So, the output is A times X i prime. And let us remember that all of these quantities X i prime, X i, X f, X o are phasors.

Now, this is our output. So, X o is equal to A times X i prime; and part of this X o namely beta times X o is feedback here as X f. So, X f is beta times X o that gets added to the amplifier input X i and that produces X i prime. So, X i prime is X plus X f because we have this plus signs here, so that completes the picture. And let us now look at how X o and X i are related. Let us start with X o which is A times X i prime. What is X i prime it is X i plus X f, so we put that here. And X f is beta times X o. So, we substitute that over here and finally, end up with A times X i plus A beta times X o.

Now, this term which contains X o can be taken to this other side, and then that gives us a relationship between X o and X i. And the ratio of X o and X i is called A f that is the amplifier gain with feedback and that is given by A divided by 1 minus A beta. It simply follows from this equation here. Since A and beta will generally vary with omega, we rewrite A f as A f as a function of j omega to indicate that it is a function of omega equal to A of j omega the amplifier gain divided by 1 minus A of j omegA times beta of j omega, this network is frequency sensitive. So, it definitely has frequency dependence and that is denoted by this beta as a function of j omega.

Now, what happens if A times beta becomes 1, the denominator will become equal to 0, and then A f will tend to infinity. And then what happens then we get a finite X o which is equal to A f times X i even if X is very, very small or 0 in the limiting case. So, we are getting an output even without supplying an input. In other words, we can remove X i, So, this part can be removed altogether and still get a nonzero X o and that is the basic principle behind sinusoidal oscillators.

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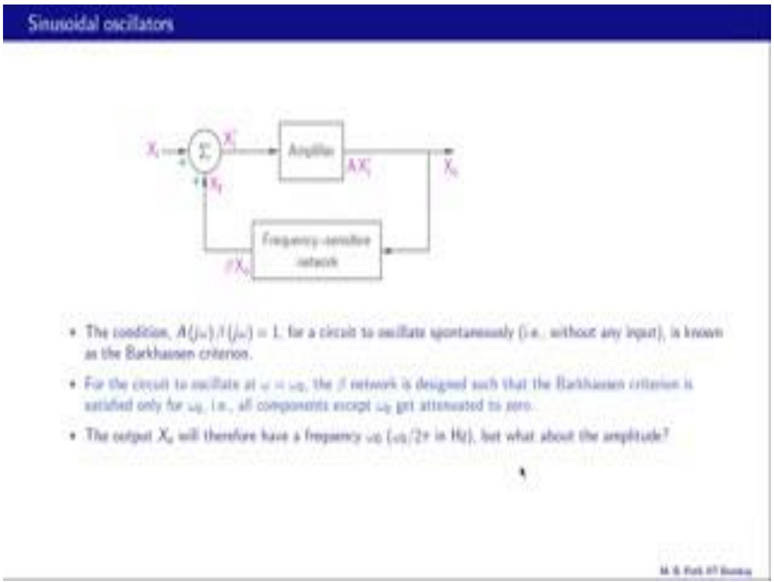

What is the condition for oscillation, we should remember that that is A times beta at the frequency of oscillation should be equal to 1. So, let us make some important points, the condition A times beta equal to 1 for the circuit to oscillate spontaneously that is without any input is known as the Barkhausen criterion. For the circuit to oscillate at a certain frequency omega equal to omega 0, the beta network this network here is designed such that the Barkhausen criterion is satisfied only for that specific frequency omega 0 that is all other components except omega 0 we will get attenuated to 0, and that is how we get purely a sinusoid at the output. So, the output X o will therefore have a frequency omega

0 or if you want it in hertz then it is omega 0 by 2 pi, but we have not really said anything about the amplitude. So, that is the next question we want to address.

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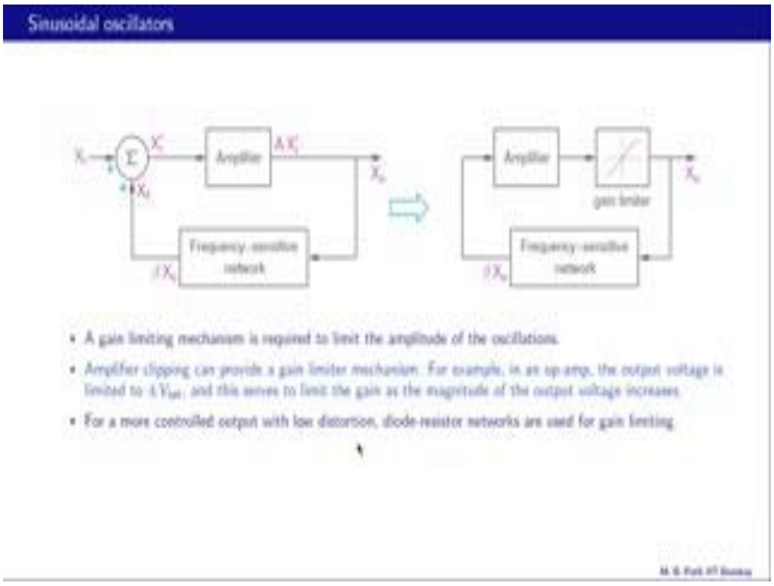

Here is our feedback amplifier; and as we have seen this circuit will oscillate that is we can even remove this X i and still get a sinusoidal output ,if we satisfy the Barkhausen criterion which is a of j omega this A times beta of j omega equal to 1. So, the product of these two should be equal to 1 and that will happen only at one specific frequency let us call that omega 0 and that is what we will get at the output. So, X o will be a sinusoid of frequency omega 0, but we have not said anything about the amplitude, and let us discuss that now.

Here is a block diagram, which illustrates how we can limit the amplitude of the oscillations. And notice that we are not showing X i in this block diagram. We assume that the Barkhausen criterion has been met, the circuit is oscillating freely and therefore, an input voltage is not required, so that is 0 and X f which is equal to beta X o is connected directly to the amplifier like that.

Again limiting mechanism is required to limit the amplitude of the oscillations. Here is a schematic diagram showing gain limiting. What do we have here, we have V o versus V i relationship indicated in this graph, let us say this is our V i and that is our V o. In the central part we have a slope of one and here the slope is smaller. So, what it means is if the amplitude becomes large then it tries to reduce the output voltage. In practice, these are not implemented separately sometimes and we might see that these two are combined, but as a schematic representation, this is adequate for us.

Now, there is some natural gain limiting mechanism in amplifiers. Amplifier clipping can provide a gain limiter mechanism. For example, in an op-amp, the output voltage is limited to plus minus V sat as we have already seen. And this serves to limit the gain as the magnitude of the output voltage increases. But what is normally done is a separate gain limiting network is used. For a more controlled output with low distortion, diode-resistor networks are used for gain limiting. And let us take some examples of such networks to understand what is happing.

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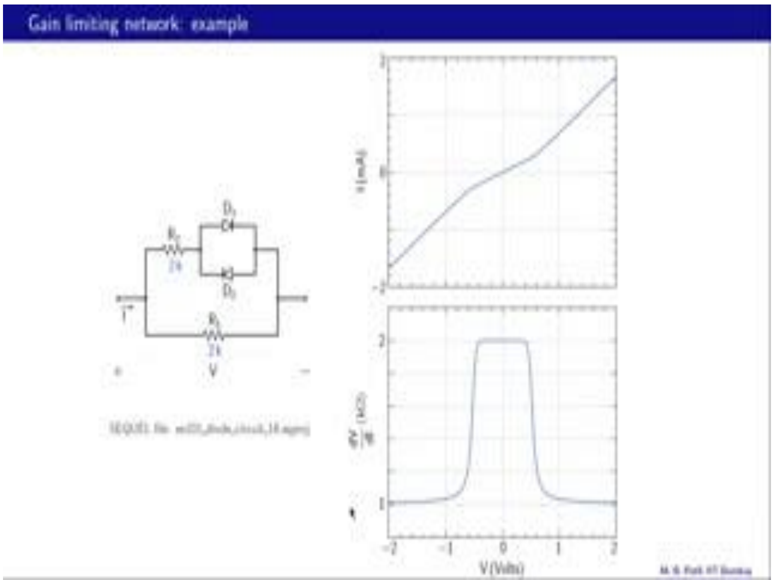

Here is a gain limiting network example, and exactly how we are going to use it we will not comment on right now, we will look at some oscillator circuits later and see how that fits in. Right now, our interest is what this I looks like as a function of V. When these diodes are not conducting the only resistance in the picture is this R 1 and therefore, I versus V will have a slope of 1 over R 1. As we increase V at some point D 1 will turn on and now we have two current paths that and that and that will cause a change in the slope of the I versus V relationship. Similarly, if we make V negative and keep increasing it in negative direction at some point D 2 will turn on and then we will have this current as well as that current and that again will change the slope of the I versus V relationship.

So, let us now look at what the I-V looks like. Here is the I versus V relationship - the top plot. Now, if you look at this central region that is where the diodes are not conducting and the only resistance then is R 1 and that slope is 1 over R 1. Remember that we are plotting I versus v. So, the slope will have units of conductance. Now, as we increase V in the positive direction around here D 1 turns on and now what happens is R 1 and R 2 come in parallel. So, the slope now becomes 1 over R 1 parallel R 2, and since R 1 parallel R 2 is smaller than R 1 this slope is larger than this one. So, the slope has increased. And the same thing happens also in the negative direction. As we increase V in the negative direction, at some point D 2 turns on, and again the slope increases over here compared to this slope.

In this bottom plot, you have plotted d V dI that is the derivative of this voltage with respect to this current in kilo ohms as a function of the applied voltage V - this V here. Now, in the central region when the diodes are not conducting this branch is not there and the only resistance then is this R 1. And therefore, what we expect for d V d I is simply R 1 which is 2 k and that is what we see over here that is 2 k. Now, as we increase V in the positive direction at some point D 1 starts conducting, and this is a real diode it is not a diode which starts conducting abruptly at 0.7 volts. So, therefore, the variations are smooth as shown here.

When this diode starts conducting, the net incremental resistance is now reduced because we have now two parallel current paths and then the resistance goes down. Eventually what happens is the diode is conducting so heavily that its own resistance is very small 0, and then all we see is R 1 and R 2 in parallel and that is what you can see over here. What is R 1 parallel R 2, it is 1 k and that is exactly what we are seeing over here. And the same thing happens also in the negative direction somewhere here D 2 starts conducting and the resistance the incremental resistance d V d I falls and eventually becomes equal to 1 k.

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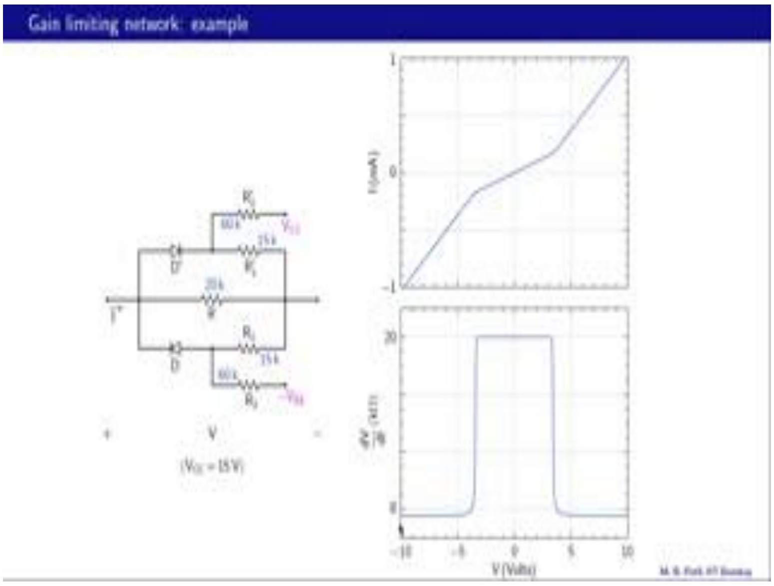

So, let us remember this picture, when we talk about oscillator circuits, this picture will be relevant in limiting the gain. Second example, we have two diodes here D and D prime. And we want to look at how this current I varies as a function of this voltage. This V C C is power supply equal to 15 volts, minus V E E is minus 15 volts. And the resistance values are indicated here in the figure.

Now, the way this circuit works is for small voltages neither D is on nor D prime is on, and the only resistance in the circuit is this R here, and that is our conduction paths. And when D prime and D are both off, this node is at 15 divided by 74 times V C C with respect to this node here simply by voltage division. Let us say we are taking this as reference a ground with respect to that ground, this node voltage is 3 volts when D prime is not conducting.

Now, if we keep increasing V, at some point this voltage will become larger than 3 volts and it will become 3 plus V on of this diode and now the diode will start conducting. And now some additional resistors are coming in parallel with R and the net resistance will then go down, so that is roughly how this circuit works. And similarly, when we increase V in the negative direction at some point this diode D turns on, and once again the slope of the I versus V relationship changes.

Here is the current versus voltage plot the top one. In this central region, D and D prime are both off, and the only resistance in the circuit is then this 20 k. And therefore, this slope is 1 over 20 k. At this point D prime turns on and that is between 3 volts and 4 volts as we expect. Now, there is this additional current path, and therefore the net resistance goes down and therefore the slope which goes as 1 over R increases. The same thing happens in the reverse direction, somewhere here D turns on and the slope increases.

And in fact, when we were looking at diode circuits we have seen circuits like this and you should be able to actually find out what this I versus V should look like theoretically. And in that calculation, we can treat this D prime and D to be ideal diodes with a turn on voltage of let us say 0.6 volts or 0.7 volts, and you should be able to calculate all of these slopes. Now, d V d I in kilo ohms is shown in this bottom plot as a function of the applied voltage V. In this central region, since R is the only resistance in the picture we get d V d I equal to R which is 20 k that is what we see here.

As D prime starts conducting the resistance starts going down and when D prime conducts sufficiently strongly. Finally, what happens is this 20 k, 15 k and 60 k, they all come in parallel and that gives us this resistance here. And that turns out to be something like 7.6 k or so. And the same thing happens also in the negative direction. Here D turns on, and then finally 20 k, 15 k and 60 k come in parallel and that gives us this resistance value here.

To conclude, we looked at a Schmitt trigger circuit in which the threshold voltages can be adjusted using a reference voltage. We then started our discussion on sinusoidal oscillators and described the basic principle of operation for these circuits. In the next class, we will consider specific examples of sinusoidal oscillators. So, see you next time.