Basic Electronics
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Lecture - 51
Schmitt triggers (continued)

Welcome back to Basic Electronics. In the last class we have seen how a Schmitt trigger works we will now look at some applications of the Schmitt trigger we will see the advantage of using a Schmitt trigger as a comparator we will also look at the use of a Schmitt trigger in wave form generation. So, let us begin.

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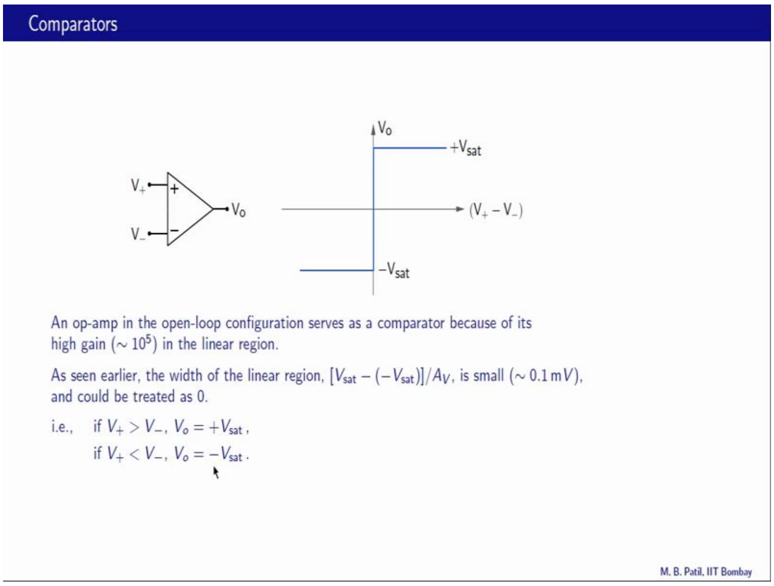

We will now look at some applications of Schmitt triggers, but before that let us talk about comparators, what is a comparator? It has 2 inputs plus and minus and 1 output, if V plus is higher than V minus then the output is high and if V minus is higher than V plus then the output is low and this figure here shows the relationship between V o and V plus minus V minus.

Now this relationship looks familiar to us because we have seen that in the context of op-amp. An op-amp in the open loop configuration can serve as a comparator because of its very high gain something like hundred thousand in the linear region. This is our linear region and as we have seen the gain in the linear region is very high. As seen earlier the width of the linear region this width here is V sat minus minus V sat divided by a V and that is very small something like 0.1 millivolts and we can treat that as 0. So, in short if V plus is greater than V minus we can say that V o is plus V sat and otherwise V o is equal to minus V sat.

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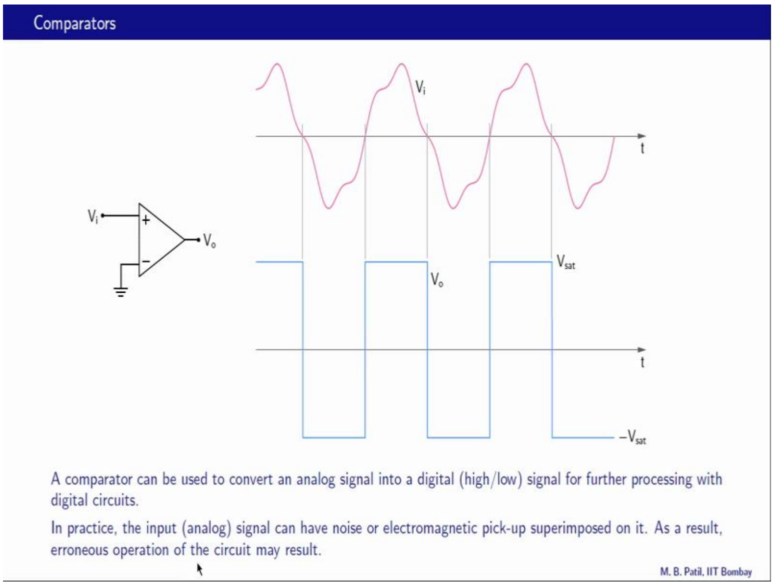

Here is an example of how a comparator works. This is a signal V i which is applied here V minus is at 0 grounded and if V plus which is the same as the V i is positive then V o is high otherwise it is low. So, in this region V o is high in this region V o is low and so on and these levels actually need not be plus V sat and minus V sat there are comparators which can give levels of 0 and some positive voltage, but that is not important for our discussion. So, a comparator can be used to convert an analog signal for example this one into a digital that is high low kind of signal this 1 for further processing with digital circuits and we are going to look at digital circuits later.

In practice the input analog signal can have noise or electromagnetic pick up superimposed on it and because of that erroneous operation of the circuit may result and let us see an example of that situation in the next slide.

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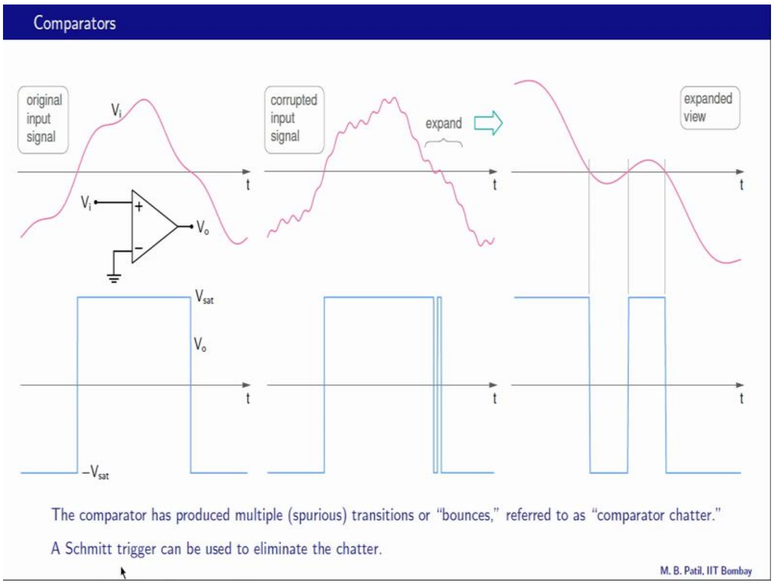

So, this is the situation we consider this is our input voltage and once again we have connected the minus input to ground and the plus input to V i. So, the expected output is given here when V i is positive we expect the output to be plus V sat and when V i is negative we expect the output to be minus V sat, here as well as here. What happens with practice is that the input signal is not always clean there could be some noise or electromagnetic pick up riding on it and therefore, the original signal might get corrupted and might look like this for example.

And because of that instead of one transition that we expect from plus V sat to minus V sat we might have multiple transitions as shown here and let us expand this part to get a clearer picture of this situation. So, let us expand that part over here. So, this is our input signal and instead of crossing 0 only once as in this case it is crossing it here and then here and then here again and because of that the output transition is not just 1, but 1 2 and 3 and this is definitely not desirable. So, what has happened is the comparator has produced multiple spurious transitions or bounces which are referred to as comparator chatter. It turns out that we can use a Schmitt trigger to eliminate this chatter and let us see how we can do that in the next slide.

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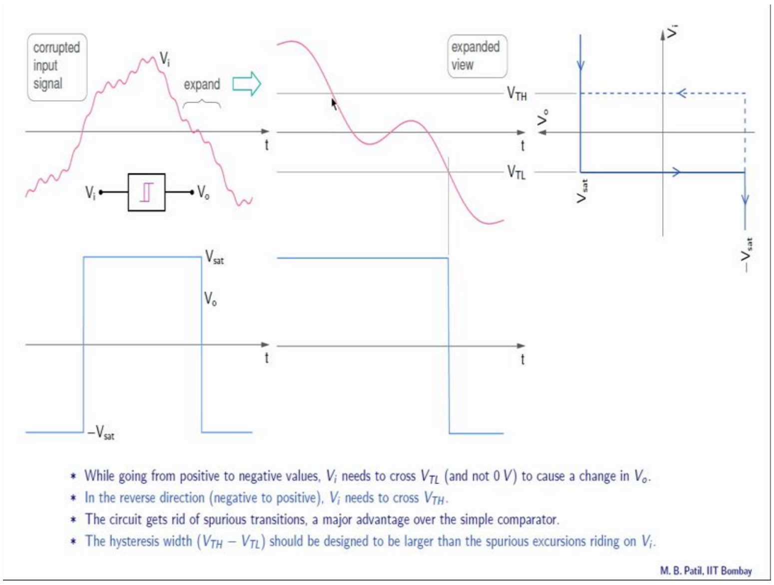

Let us now see how replacing the comparator with the Schmitt trigger helps in the situation. So, here is our corrupted input signal same as in the last slide and now this Schmitt trigger gives us only one transition and let us try to understand how that is possible. So once again let us expand this part to get this V i versus time curve here and it has crossed zero, three times 1 2 and 3, but that has resulted in only one transition in the output that 1 and let us now try to understand why that happened.

So, here is our V o versus V i relationship for the Schmitt trigger and it looks a little different because our V i axis is now drawn vertically, but it is the same as we have seen earlier this is V TH, this is V TL, this is the high V o level V sat and this is the low V o minus V sat. When the input voltage is here we are here on this V o versus V i relationship and now what is happening as time proceeds this input voltage is coming down so we are going in that direction and when is the output going to change the output is going to change not at V TH, but at V TL; that means, the output will only change when the input voltage reaches this point and that is exactly where this transition is occurring.

Now what happens in between is not really important even if you had several transitions in this region it does not really matter because the input voltage has to cross this V TL level to produce the transition at the output. So, that is how these spurious transitions are taken care of.

Let us summarize while going from positive to negative values V i needs to cross V TL and not 0 volts to cause a change in V o. So, we are going from positive to negative it has to cross this point which is V TL and only then the change in output will happen. In the reverse direction negative to positive V i need to cross V TH negative to positive. So, we are going like that and now we have to cross this level V TH for the output to change.

The circuit gets rid of spurious transitions which is a major advantage over the simple comparator. The hysteresis width V TH minus V TL should be designed to be larger than the spurious excursions riding on V i this is our hysteresis width and we should design it such that it is larger than these excursions which are adding on the input voltage then we will not have this problem of multiple transitions.

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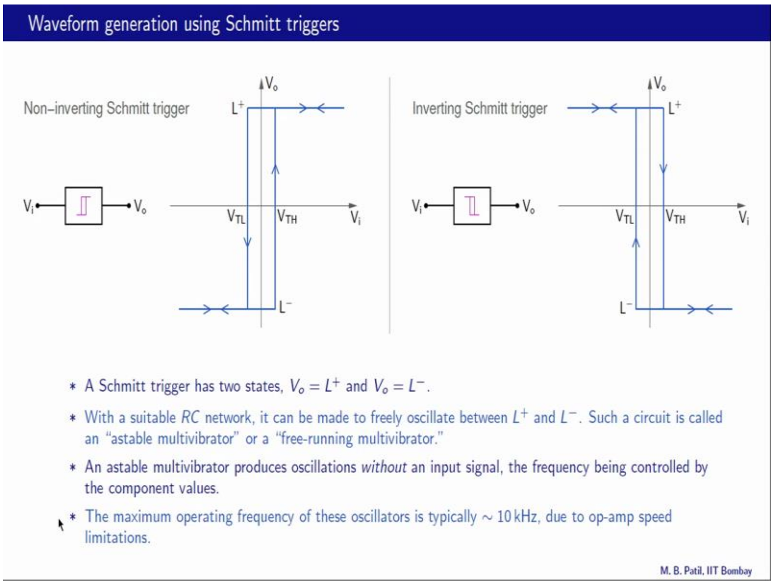

We will now look at another application of Schmitt triggers and that is to generate wave forms. In particular square wave output voltages here is a summary of the V o versus V i relationship for a non-inverting Schmitt trigger and an inverting Schmitt trigger and here are the symbols.

Let us make few important points a Schmitt trigger has 2 states V o equal to L plus and V o equal to L minus, L plus L minus, L plus L minus. With a suitable RC network connected to this Schmitt trigger it can be made to freely oscillate between these 2 levels L plus and L minus and such a circuit is called astable multivibrator or free-running multivibrator. An astable multivibrator produces oscillations without an input signal the frequency being controlled by the component values such as resistance or capacitors and we should remember that the maximum operating frequency of these kinds of oscillators is typically about 10 kilohertz and that is because of op-amp speed limitations. As we have seen earlier op-amp has a Fahrenheit slew rate and therefore, this maximum operating frequency is limited.

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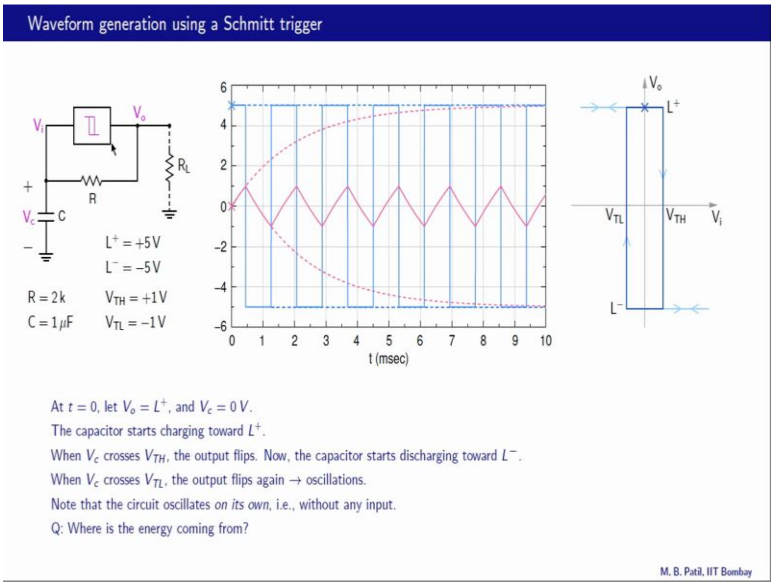

Let us take a look at this circuit, what do we have here? We have an inverting Schmitt trigger and that is its V o versus V i relationship and its reproduced here, this is the high tripping point V TH, low tripping point V TL - L plus is the high level of V o and L minus is the low level of V o, this axis is V o this axis is V i, V o is here and V i is here. So, V i is the same as the capacitor voltage.

Let us take some numbers R equal to 2k, C equal to 1 micro Fahrenheit L plus plus 5 volts L minus minus 5 volts V TH plus 1 volt V TL minus 1 volt. So, this is plus 1 volt here minus 1 volt, plus 5 minus 5 and as we will discover this circuit oscillates between high and low and let us see how that happens.

Let us start at t equal to 0 with V o equal to L plus and V c equal to 0; that means, the capacitor is uncharged and V c and V i are the same. So, our V c equal to V i equal to 0 and our V o is L plus. So, we are right here that is the data point that we have right now at t equal to 0, what happens now? This input current is 0, this V o is plus 5 volts capacitor voltage is 0. So, the capacitor is going to start charging towards V o that is plus

5 volts and the time constant of course, is R times C is only one R here and that are 2 k times 1 micro or 2 milliseconds.

Note the scale here this entire period is 10 milliseconds. So, let us show this charging process that is how the capacitor will charge. Since the time constant is 2 milliseconds in about 5 time constants that is 10 milliseconds it would charge towards 5 volts and the charging process would be almost completed. Now it does not quite reach there and let us see why. Let us look at what is happening with respect to this V o V i relationship we started of here at t equal to 0. So, our V c or V i was 0 our V o was plus 5 and now this capacitor has started charging, what does it mean? That means, V i has started increasing V i and V c are the same, so therefore, we are moving like that.

And what happens when V i crosses V TH the output flips like that and now what happens is this V o has become minus 5 volts and the capacitor will now start discharging and will eventually reach minus 5 volts, but again that does not happen why? Because as the capacitor discharges we are moving like that V o is minus 5 and V i is decreasing so we are moving in that direction and when we cross V TL again the output is going to change and this process is going to result in oscillations like that.

So, at this point the output changed to plus 5 again, the capacitor now starts charging again towards 5 volts like that and so on. So, this process just keeps repeating and we have oscillations. So, our V o is a square where plus 5 to minus 5 and we get this kind of wave form for V c or V i.

Note that the circuit oscillates on its own that is without any input there is no input anywhere for this circuit. Question, where is the energy coming from, what is the answer to that? Remember there is an op-amp sitting inside. So, that is where the energy is coming from specifically the power supply of the op-amp.

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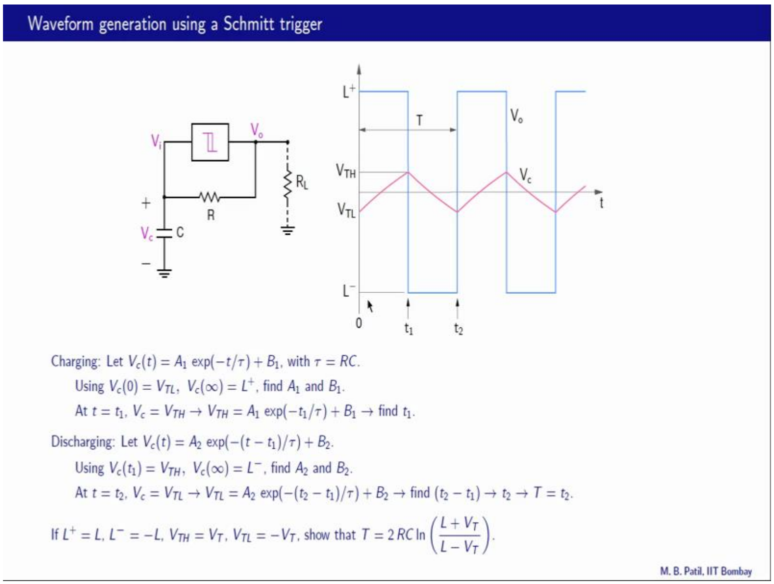

Let us now find the period of oscillation here are the wave forms V o going from L plus to L minus and V i or V c going from V TL to V TH. If you recall in the last example we had V TL is equal to minus 1 volt V TH is equal to plus 1 volt L minus was minus 5 volts and L plus was plus 5 volts, all right. So, where do we begin let us consider this portion, this is the charging process and the capacitor is going to charge towards L plus and that process can be described by this expression V c t equal to A 1 e raise to minus t by tau plus B 1 where tau is simply R times C. What is V c at 0? This is our t equal to 0 to V c is V TL. What is V c at infinity? At infinity this capacitor voltage would reach L plus. So, that is our V c at infinity.

Now, using these 2 conditions we can find A 1 and B 1, you are suppose to do it as homework and now let us use the condition that at t equal to t 1 this point V c is equal to V TH. So, we substitute V c is equal to V TH in this expression A 1 e raise is to t 1 by tau plus B 1, A 1 and B 1 are already known from these conditions and that gives us t 1.

Let us now look at the discharging transient this part at t equal to t 1 the capacitor voltage is equal to V TH and then it starts decreasing and it would have gone all the way to L minus as t tends to infinity. However, that does not happen because at t equal to t 2 the output voltage flips and let us now describe this part of the transient in this equation here V c of t equal to A 2 e raise to minus t minus t 1 by tau and this amounts to taking this t 1 as the reference or the origin and that turns out to be convenient plus B 2.

Now, to find A 2 and B 2 we need 2 conditions on V c of t what are those 2 conditions? One at t equal to t 1 V c is V TH. What about the second condition? As t tends to infinity V c would have reached L minus, so that is the second condition. So, using these 2 conditions we can find A 2 and B 2 and now we can use the condition that at t equal to t 2 V c is equal to V TL. So, we substitute V TL over here and t 2 over here and then we get V TL equal to A 2 e raise to minus t 2 minus t 1 by tau plus B 2 and A 2 and A 2 of course, are already known from here, all right. So, with this equation we can now obtain t 2 minus t 1, t 1 is already known and therefore we can get t 2 and t 2 is the same as the time period T.

So, let us now take a special case let us say that L plus and L minus are equal in magnitude for example, this maybe 10 volts this may be minus 10 volts and V TH and V TL are also equal in magnitude for example, this may be 2 volts and this maybe minus 2 volts. In that case we can show that this time period that is a period of oscillation is given by 2 RC times log L plus V t divide by L minus V t, where L is this L plus and V t is the same as V TH. Now you are encouraged of course, to go through all of this algebra and arrive at this result.

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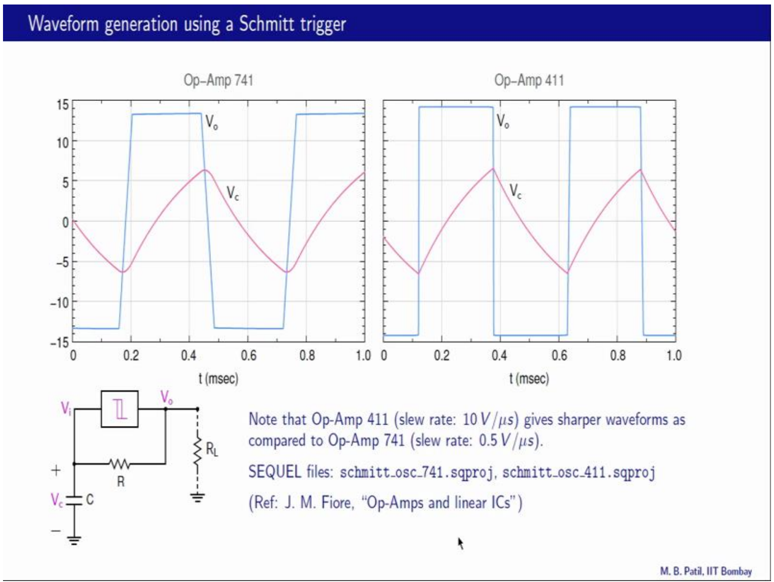

If you hookup this circuit in the lab you will realize that it cannot be pushed to arbitrarily high frequencies and that is because op-amps have a finite slew rate for example, op-amps 741 has a slew rate of 0.5 volts per micro second. This is the wave form obtained with op-amp 741 and as we can see it is not as sharp as we would expect theoretically, we have these slopes here. Whereas, if we use another op-amp with a higher slew rate like op-amp 411 which has much higher slew rate 10 volts per micro second then we can get sharper wave forms. So, that is an important point and we should remember that if we want to implement that in the lab or for some application.

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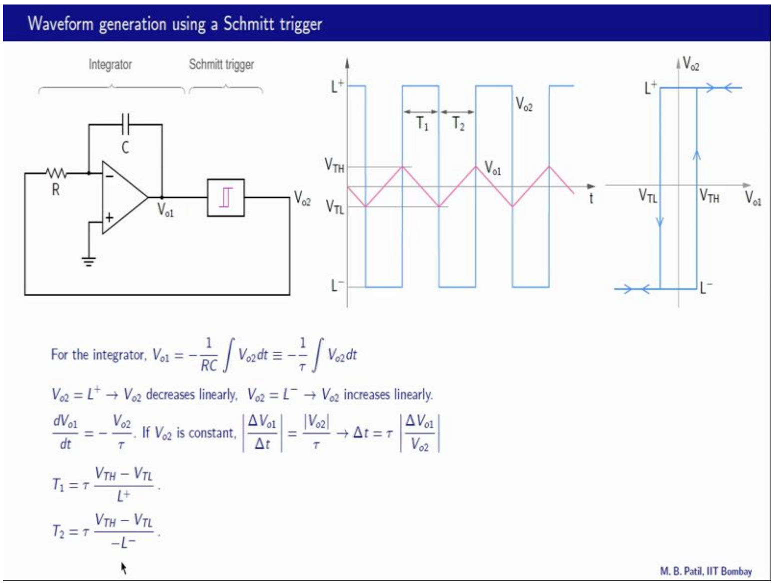

Here is another oscillator circuit that uses Schmitt trigger. It has an interrogator and a Schmitt trigger connected in a circular fashion that is the output of the interrogator goes as the input of the Schmitt trigger and the output of the Schmitt trigger is the input of the integrator. The V o versus V i relationship for the Schmitt trigger is shown here, it is a non-inverting Schmitt trigger, V TH and V TL are the tripping points and the L plus and L minus are the high and low output voltage levels. This axis is the output of the Schmitt trigger and in this case it is V o2 and this axis is the input of the Schmitt trigger and in this case it is V o1.

So, note that V o2 servers as input for the integrator. These are the wave forms that are V o 2 the blue 1 and that is V o1 and V o1 is a triangular wave form in this case as opposed to the capacitor voltage wave form that we saw in the last circuit. Let us look at how this circuit works let us start with the integrator. For the integrator we have V o1 which is the output equal to minus 1 over RC integral V o2 dt, V o2 is the input for the integrator and we rewrite that as minus 1 over tau integral V o2 d t if V o2 is positive V o1 will decrease and V. If V o2 is negative then V o1 will increase and that is because of this negative sign.

So, let us consider the case where V o2 is positive let us say this interval marked t 1 here. So, here V o1 is decreasing because V o1 is positive and what is happening in terms of this V o versus V i relationship for the Schmitt trigger? V o2 is 5 so we are here and V o1 is decreasing so we are going in that direction. When we cross V TL output is going to flip from high to low and that is what happens here.

When V o2 changes its sign as it goes from L plus 2 L minus there is a change of sign here and therefore, V o1 now starts increasing that is what we are seeing over here and in terms of this plot what is happening is V o2 is negative L minus so that is here and V o1 is increasing so we are going in that direction. And now when we cross V TH V o2 will change once again from negative to positive. So, that is what happens at this point, V o2 changes from L minus to L plus and this process keeps repeating and that is how we get oscillations.

Let us now compute the period of oscillation what is the period of oscillation? T that is equal to T 1 plus T 2, we can compute T 1 and T 2 individually and then add the two. And an easy way to do that is to just differentiate this equation when we do that we get d V o1 dt minus V o2 tau and if V o2 is constant then we can write delta V o1 by delta t equal to mod of V o2 by tau just taking only magnitudes here. That gives us delta t equal to tau times delta V o1 by V o2 and now we can apply that to each of these intervals T 1 as well as T 2 and that gives us T 1 equal to tau times V TH minus V TL that is our delta V o1 divided by V o2, V o2 is L plus at that time. What about T 2? Similar delta V o1 is once again the same this difference and V o2 is now L minus and of course, we have to take the magnitude of that so therefore, we have put a minus L minus here, so that is T 1 and T 2. So, the period is T 1 plus T 2 and that gives us the frequency equal to 1 over T.

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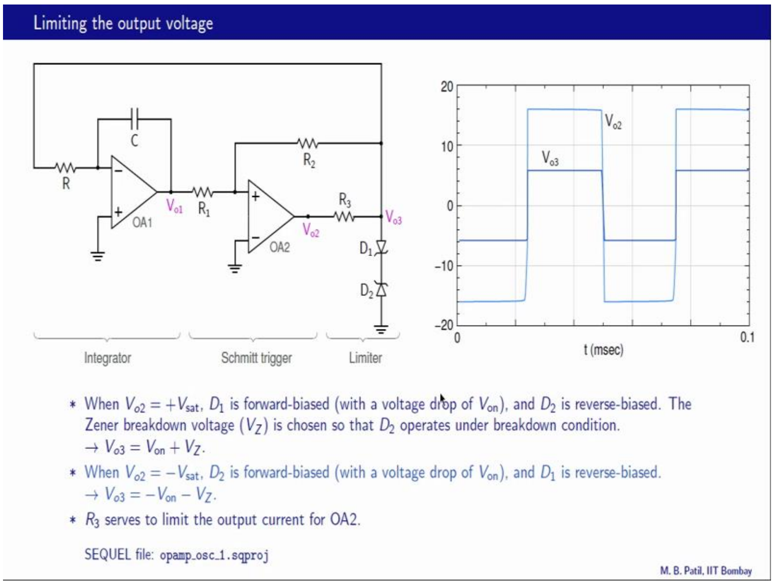

Sometimes we are interested in limiting the output voltage that is produced by this Schmitt trigger which we call V o2 in our previous slide and that can be done using this thinner pair and we have looked at this thinner pair and seen how it works as a voltage limitor when we were talking about diodes. When V o2 is high let say this is our V o2 level the high level then D 1 conducts in the forward direction, D 2 conducts in the reverse breakdown mode and then V o3 this output voltage is V on plus V z, V on appearing here and V z appearing here. When V o 2 is minus V sat this level then what happens is T 2 conducts in the forward direction D 1 conducts in the reverse built on mode. So, V on appears here V z appears here and the output voltage V o3 is minus V on minus V z, that level.

Now, let us look at the purpose of R 3 and that is to limit this current that we draw from this second op-amp. What is the voltage that is appearing across R 3? It is the difference between V o2 and V o3 either that or that and you can calculate R 3. So, that the current that we draw from OA2 the second op-amp is within its current limits. Here is the circuit file you can simulate this circuit and take a look at the results.

To conclude we have seen the advantage of Schmitt trigger as a comparator, we have also looked at wave form generation using a Schmitt trigger. In the next class we will continue our discussion of the Schmitt triggers, until then goodbye.