Control and Tuning Methods in Switched Mode Power Converters
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Module - 04
Variable Frequency Control Methods
Lecture - 22
Hysteresis Control Methods in SMPC's

Welcome back. So, in this is lecture number 21, and here we are going to talk about Hysteresis Control Method in Switch Mode Power Converter.

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So, in this lecture, we are first going to discuss state dependent switching and limit, voltage hysteresis control and stability, then current hysteresis control and stability, and implementation method for hysteresis control, and steady state analysis. Of course, there will be MATLAB simulation as well.

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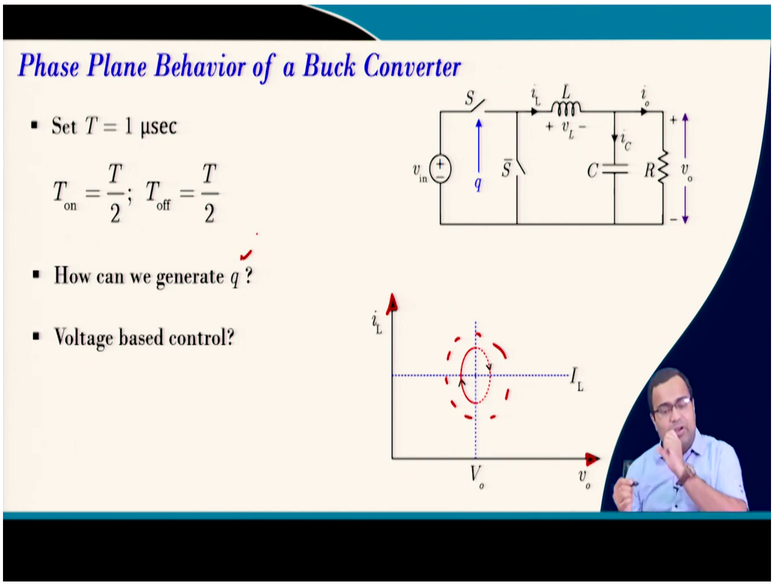

So, if we take the phase plane behavior of a buck converter, the synchronous buck converter. And this shows the trajectory, where if we set let us set T equal to 1 microsecond and we turn on the switch for T by 2 and turn off a T by 2 then how can we generate q? Because get signal; that means, here if we take just simply 50 percent on and 50 percent off that is very simple. It is like open loop converter, there is no control.

But if we want to replicate this waveform which is shown here, if we want to replicate this waveform in the phase plane, where this is the output voltage and this is the inductor current. Then, how can we generate the switching signal q? And can we do it purely based on voltage based control? Ok.

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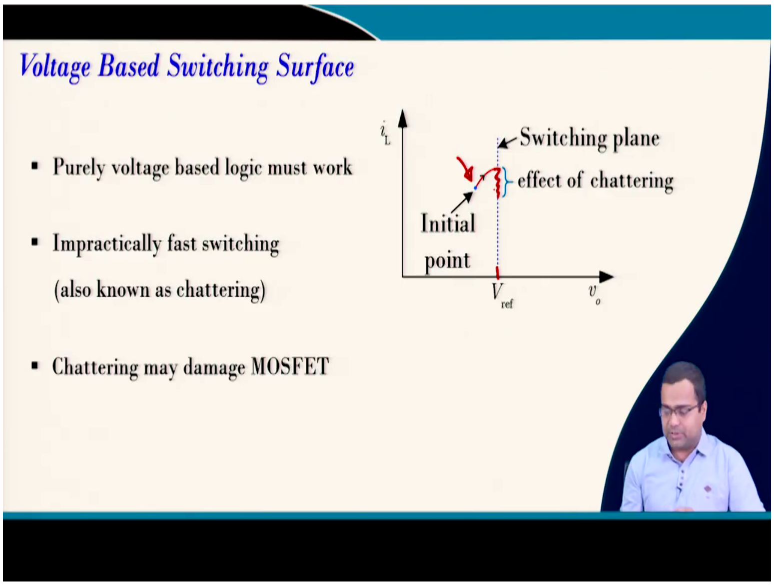

So, can we implement based on voltage based switching surface? Voltage based switching surface. So, here we are talking about again the phase plane, where x axis is the output voltage and y axis is the inductor current. And if we take this line, you know this line actually corresponding to yeah, this line corresponding to vertical line where we want to achieve the desired output voltage, reference voltage.

Now, if you take an initial condition here the simplest logic can be, if any condition like if the state the voltage is smaller than V ref, then you should turn on the switch and if the voltage is higher than V ref then you should turn off the switch. That means once it is attracted towards V ref and it crosses, you see the multiple thing; that means, we need like a turn on, off, and on and off logic based on whether the voltage is left side or right side.

And this requires infinitely fast switching action, and that is like something called chattering action. But this is, this impractical switching action is not practically possible. In fact, such fast turn on and off events can damage the MOSFET.

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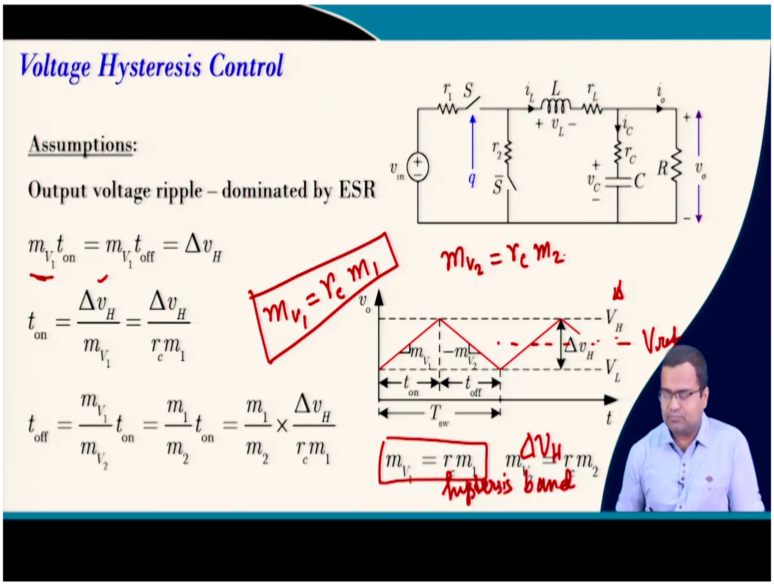

Then, what to do? So, you need to incorporate some kind of hysteresis band. And if you see the waveform, we want to achieve V ref. Let us say average is the V ref, the middle portion and we can set a higher v H which is V ref plus delta v H by 2 and v L which is v ref minus delta v H by 2, where this delta v H is my hysteresis band, this is my band, hysteresis band, ok.

Now the output voltage ripple in a DC-DC converter or a buck converter. It is dominated by ESR. So, we need to take a little larger ESR in order to capture this ripple information correctly. And also in buck converter, it can be shown if the ripple is little bit larger; that means, if the ripple due to sorry, if the ripple of the output voltage due to ESR is dominant over the ripple due to the capacitor, then the voltage ripple will be in phase with the current ripple, ok.

And then the slope of this voltage ripple, rising slope of this voltage ripple is same as that; that means, if you take the rising is m V 1 is nothing but ESR into the rising slope of the inductor current. Same thing for the falling slope.

Then, we can compute the on time and off time from this waveform by substituting the slope information and, of course, the hysteresis band. Then we can compute, ok. This is what I told r c into m. Same thing for m V 2 also; that means, m V 2 is also r c into m 2.

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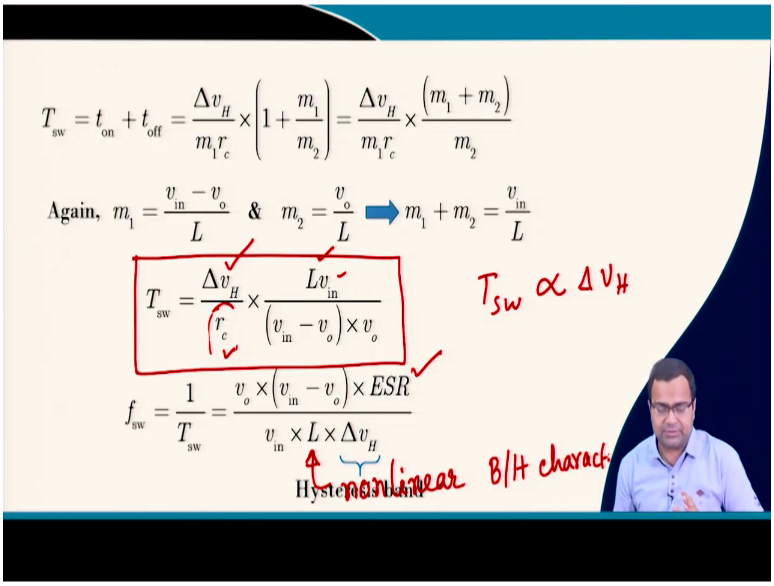

Then, we can compute the total time period and which for a buck converter if you substitute m 1 and m 2, the rising and falling slope of the inductor current, then we can get the total time period which is a function of hysteresis band ESR, inductance, then input output voltage come here.

That means, for a given input output voltage, this switching period is directly proportional to delta v H. If all other parameters, let us say ESR is more or less constant inductor is you know constant an input voltage output voltage are constant. But it is not so simple because input voltage can also vary, then you can have a variation in the switching frequency.

Also, the inductance, which actually if you take the batch characteristic of the inductance, so that non-linear characteristics of the inductance can also affect the time period drastically. That means, it is sensitive to many parameters, ok. So, it is sensitive to ESR. It is sensitive to the non-linear characteristics of the inductor non-linear B H characteristics. It is also, you know, sensitive to this, the hysteresis band, of course.

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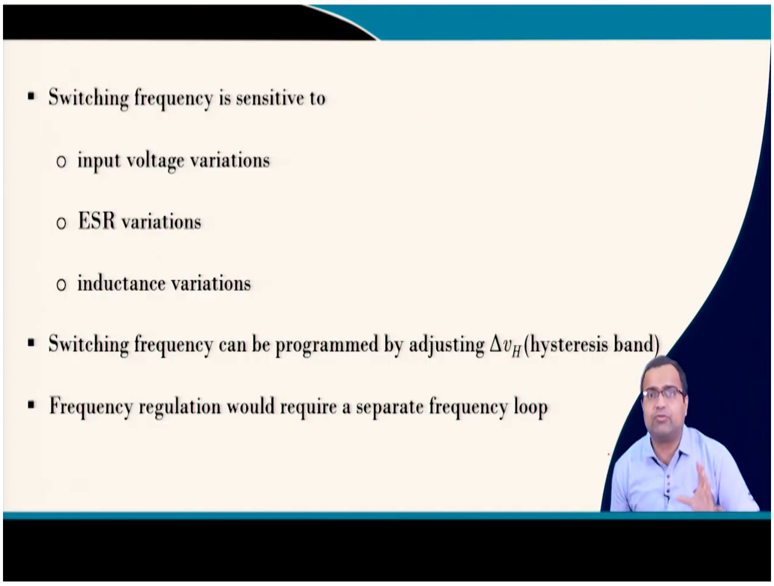

So, switching frequency is sensitive to input voltage variation, ESR variation, inductance variation, switching frequency can be programmed by adjusting delta v H. And frequency require regulation requires a separate frequency loop.

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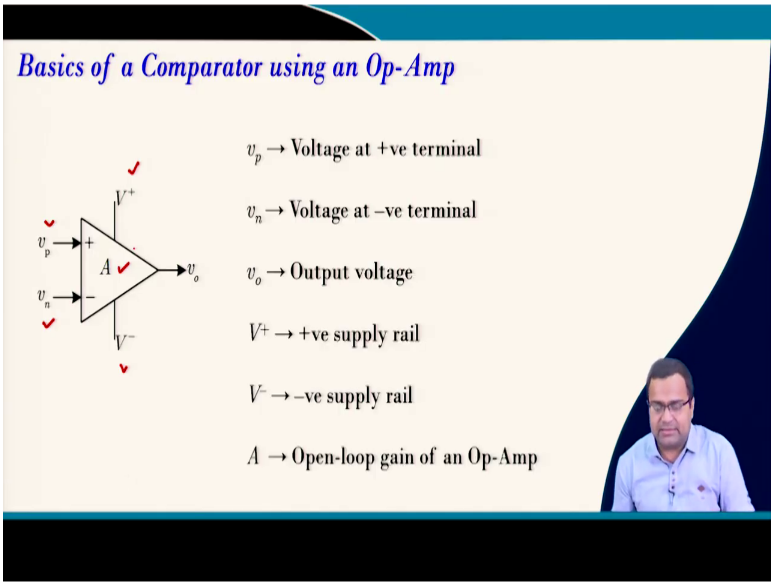

Now, so we talked about hysteresis comparator. I just want to briefly touch upon using an op amp you can actually implement a hysteresis comparator. So, if you take an op amp like in an open loop, it has a positive supply rail and negative supply rail. And this is an inverting like a negative terminal and this is the positive terminal of the op amp. It is an open loop, and A is open loop gain, ok. So, all these terminals are defined as positive, negative, supply rail, an open-loop gain of the op amp.

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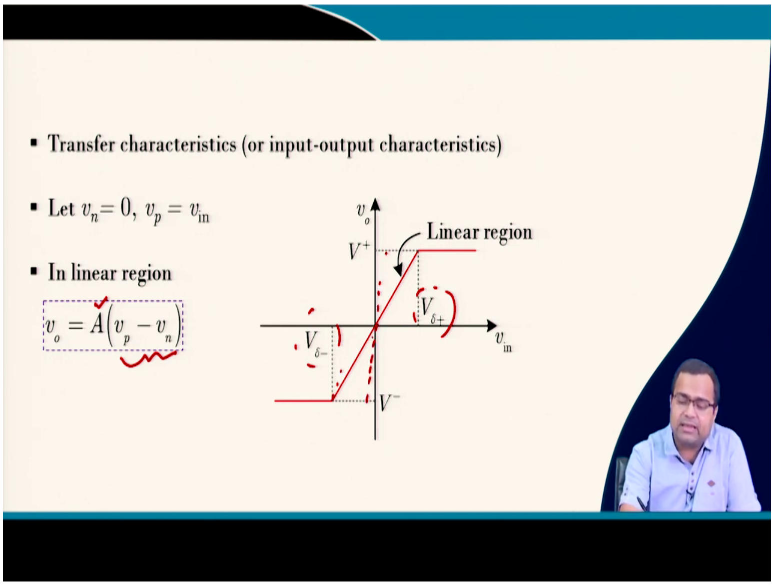

So, if you take the transfer characteristic of the op amp; that means, the input-output characteristics if we set the negative voltage to 0 and the positive voltage to v in, then what will get? The op amp will be linear in the linear region as long as the voltage output voltage of the op amp is within the supply rail, within the supply rail, ok. That means, you know this is the transfer characteristics.

Now, this region of input voltage of the op amp and the slope, particularly the slope it depends on. So, who will decide that? In the linear region, output voltage is A into v p minus v n, ok. That means, if you take this v p minus v n which is the decided by the input voltage in this case, even for the same range of input voltage, then this slope can increase.

That means we can increase this slope by increasing the open loop gain of the op amp.

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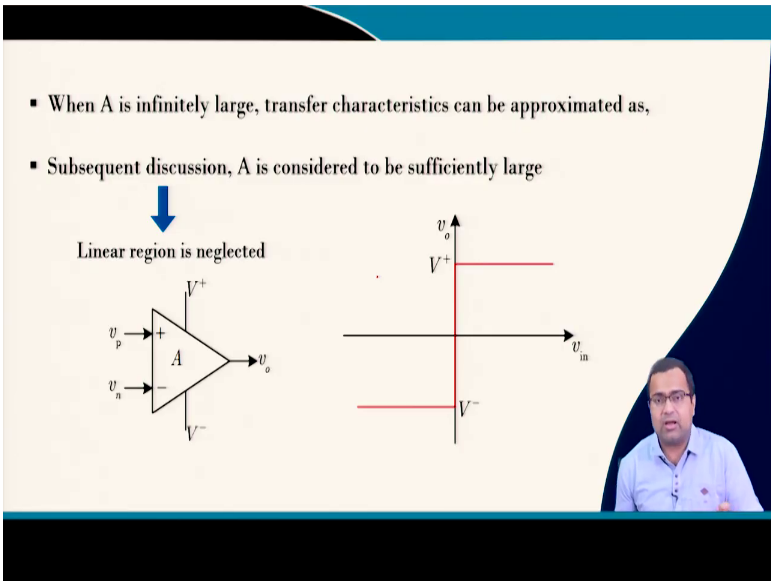

That means, if the input gain is infinitely large, then the op amp characteristic can be approximated as a pure comparator.

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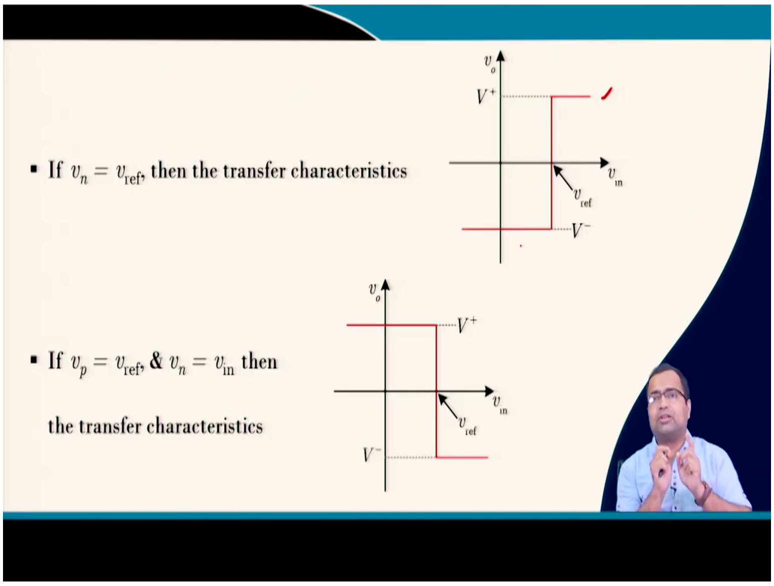

So, linear range is almost region neglected and op pump will act like a pure comparator. Now, in this condition; that means we are talking about very high open loop gain when the op amp will essentially work like a comparator in the open loop. If we take v n equal to v ref; that means, if we take the negative terminal as a v ref then we can shift the transfer characteristic.

That range can be shifted; that means, if your input voltage is higher than v ref, then it will be on the high supply rail.

If it is lower, it will be lower supply rail, ok. So, if v p equal to v ref and v n equal to v in, then we can shift. So, that means we can change the transfer characteristic based on what supply you are considering at the two terminals of the op amps.

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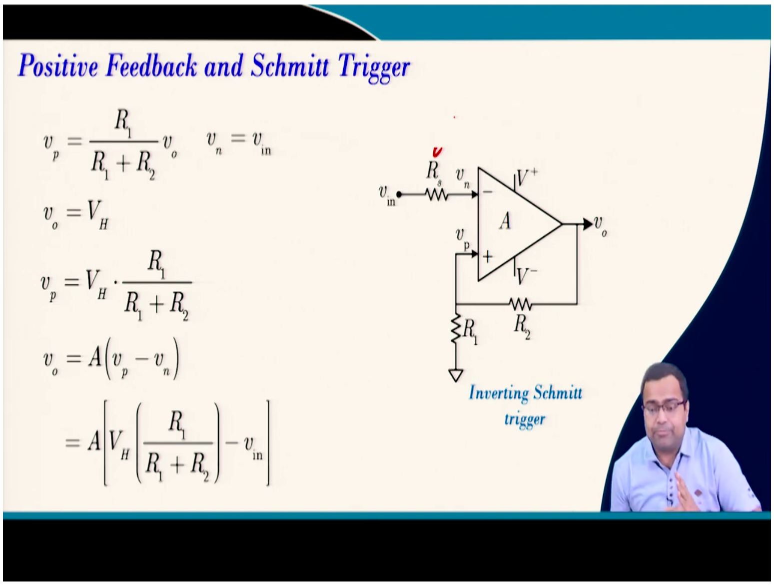

Now, if we as add a positive feedback; that means, R 1, R 2, and this source series resistance, then it actually acts like an inverting Schmitt to the circuit and that we have learnt in you know analog circuit.

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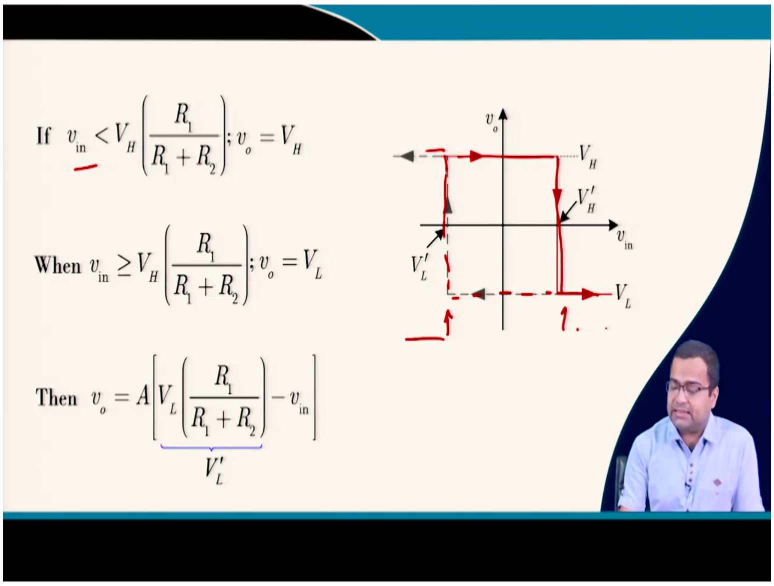

And under this condition, if we keep on deriving the output voltage expression of the op amp, then it turns out to be the output voltage of the op amp will take this form. That means, whenever it is like a hysteresis band, ok, this hysteresis band and this is the return path of the band; that means, if v in is less than; that means, if v in is less than this V L dash, then the output will be high and if v in is greater than this output will be low.

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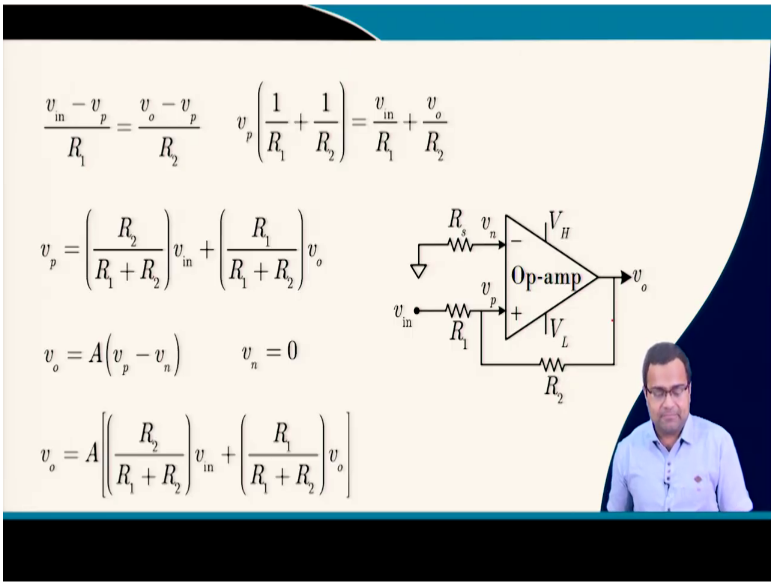

Now, If we take a non-inverting configuration, then we can in non-inverting configuration, then we can get the hysteresis comparator like this.

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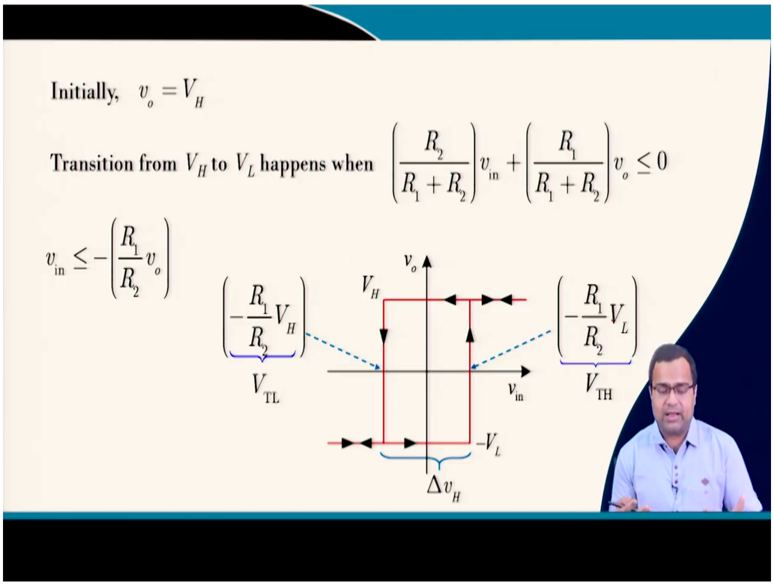

I mean, these are standard implementation of hysteresis comparator and this can be available in a standard analog circuit book. But what we are interested in how to implement; that means, this technique can be incorporated into an op amp, so that op amp can be configured as a hysteresis comparator.

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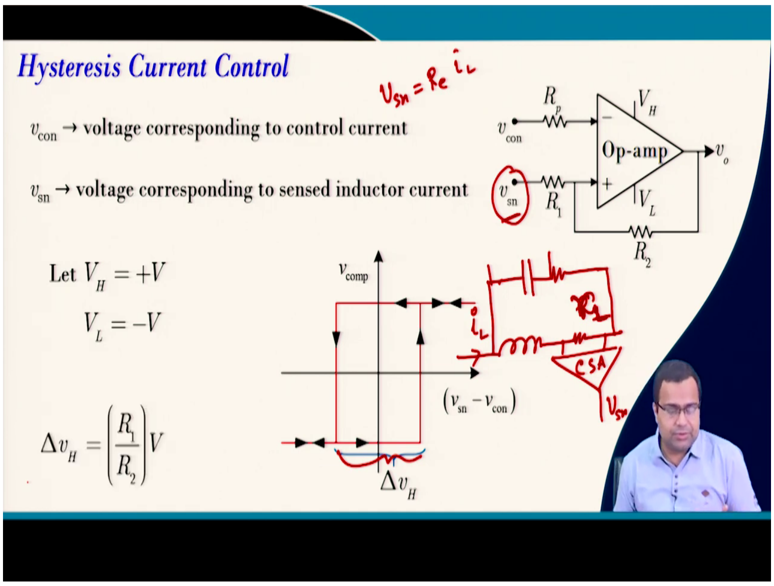

Now, in hysteresis current control, in terms of integrated circuit, in fact, this is a sense voltage which corresponds to the sense inductor current. And we talked about the sense inductor current. If you take a resistive sensor; that means, you know if we want to put the; that means, I am talking about the inductor.

If you take a direct sense resistance of the inductor and if you put a current sense amplifier, the current sense amplifier then I talked about that the V s n and this is your i L. So, V s n will be some R equivalent into i L, where R equivalent include the sense resistance multiplied by current sense amplifier gain.

There are other techniques of current sensing like a DCR sensing, where you know you do not need to put a physical resistance. This is the DCR of the inductor, and you put a capacitor and resistance in parallel.

Then, by sensing this capacitor voltage and matching the time constant, you can get nearly the same waveform of the profile of the inductor current. But in all cases, these are sensed voltages which correspond to the current, correspond to the current.

And we can set, we have discussed the Schmitt trigger or a hysteretic comparator and we can set accordingly the hysteresis band. This is my hysteresis band; what is my hysteresis band, ok. This is the hysteresis band. We can set it.

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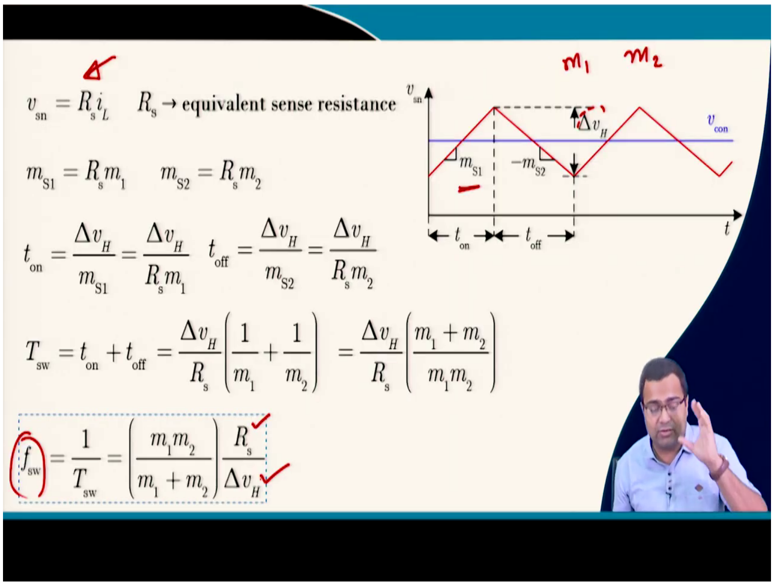

Next, if you set the hysteresis band and if you go by the sense current base approach, then what would be my switching frequency? Since it is a sense inductor current; that means, in generally m 1 is the rising slope of the inductor current and m 2 is the falling slope of the inductor current. And here m s 1, m s 2 means, m 1 into sense equivalent sense resistance, we have to multiply. So, this is the equivalent sense resistance, ok.

So, we can multiply, we can m s 2. Then, we can compute the on time and this is a voltage hysteresis band which corresponds to analogous current hysteresis because we are taking the sense inductor current, which is a voltage. So, you can compete on time, off time.

Then, we can obtain the total time period, and from there we can find out that switching frequency expression in terms of sense equivalent, sense resistance, the current hysteresis band, which is represented by equivalent voltage hysteresis and then the slopes. And if you substitute, then we can find and we will do it, ok.

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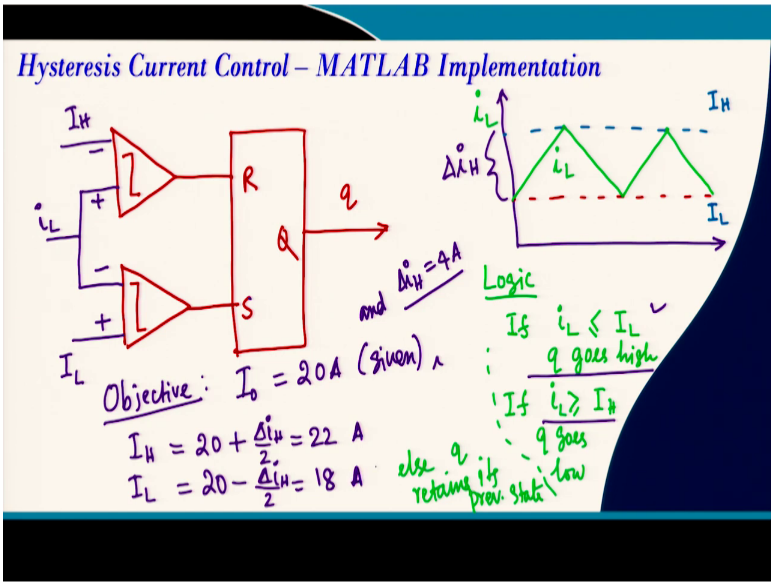

Here we are going to represent, you know we want to implement the hysteresis current control in MATLAB, ok. So, in MATLAB, we want we are not going to use a circuit implementation of Schmitt trigger and other stuff; we want to implement a simple logic of hysteresis current control.

Before we move forward, we want to show the waveform of the current, ok. So, here we are going to consider, this is one band, and this is the other band, ok. So, this is my higher band, and this is my lower band, ok. And my inductor current, we want to ensure the inductor current should be within this band. This is my inductor current.

So, this is an inductor current implementation, ok. That means, our logic should be such that. So, what is my logic requirement? Logic is that if i L is less than equal to I L, then q goes high. If i L is greater than equal to I H, q goes low. Else, else q retains its previous state, ok. Else, q retains its previous state, ok.

Now, I want to implement this logic. How can you take? I take two comparator one here, the other here, ok. These two are the ideal comparator, not hysteresis comparator. Because in MATLAB we just want to use a logical comparator, which looks like an ideal comparator. And we want to use an R S feed flow; that means, R S and Q, ok. Here, we want to consider this is my current. So, this is my current feedback, inductor current.

See, in order to turn on the switch, we know this logic should be set. So, this should be my I L and this should be my I H. And what the logic says, this logic? If i L goes below I L, that means, if this quantity become high, this is low. And what this logic says? If i L goes above, this is plus this is minus. So, this represents our implementation. And what is this band? So, this is my hysteresis band.

Now, I am going to show a MATLAB simulation where you know I want to implement a buck converter where I want to introduce two loops. First, I want to show a current, purely current hysteresis band. Let us go to the MATLAB implementation.

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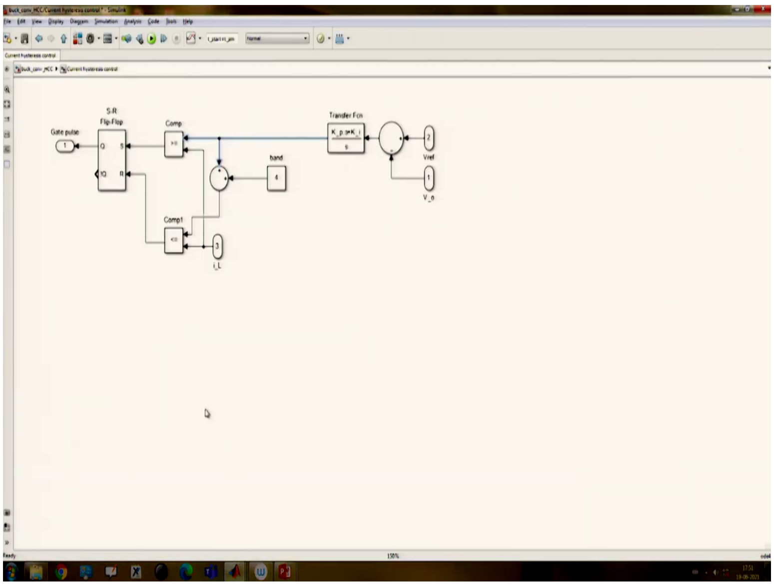

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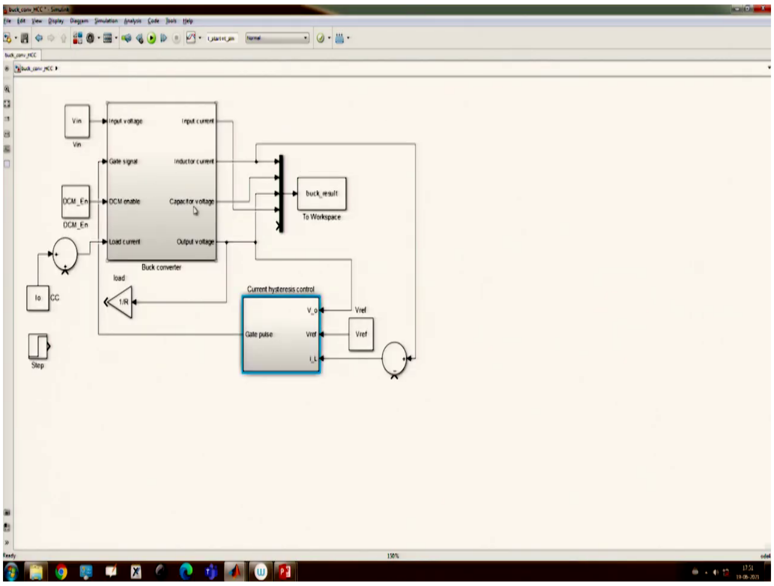

Here I am showing a current hysteresis control. Let us say I want to keep the current. So, let us see what is the load current.

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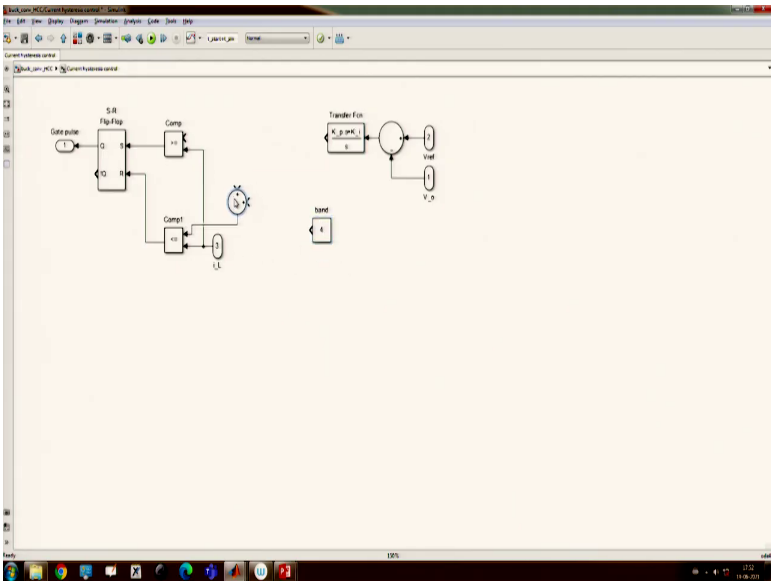

So, if I load current let us say is 20 Ampere is my load current. So, I want to maintain between; I want to put a 4 Ampere hysteresis band, if my upper limit is, that means, what is my design objective? Let us say, my objective my I load current is 20 Ampere that is given. That means, I want to achieve that is given. So, I H should be and delta I H, let us say I set it like a 4 Ampere. Then, I H should be 20 plus delta I H by 2 which is 22 and I L should be 20 minus delta I H by 2 which is 18, ok.

Now, let us see whether can we implement in MATLAB or not, ok. So, this is one logic, this is going to reset. So, this should be the peak, this should be the valley, ok. So, this is the valley where we are going to subtract, right, ok.

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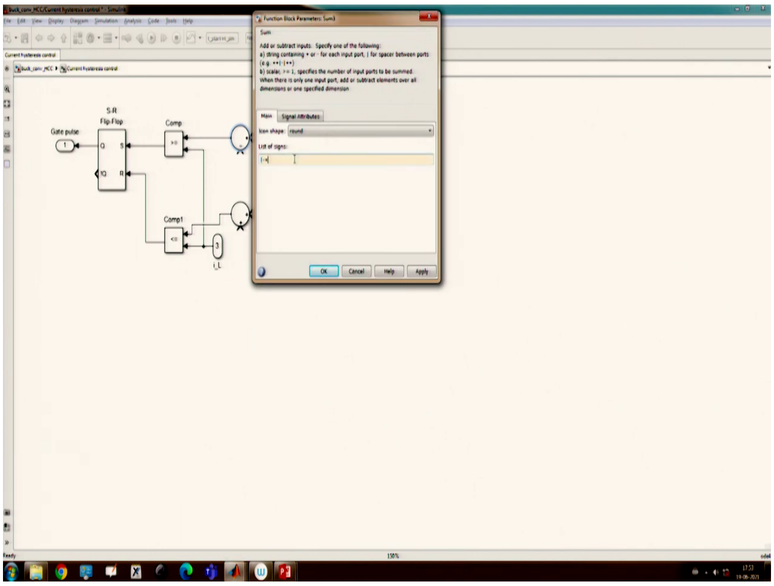

So, in both these cases, we want to, so it took already the comparator and 20 Ampere is my limit. That means, 20 Ampere is my current ref, high ref.

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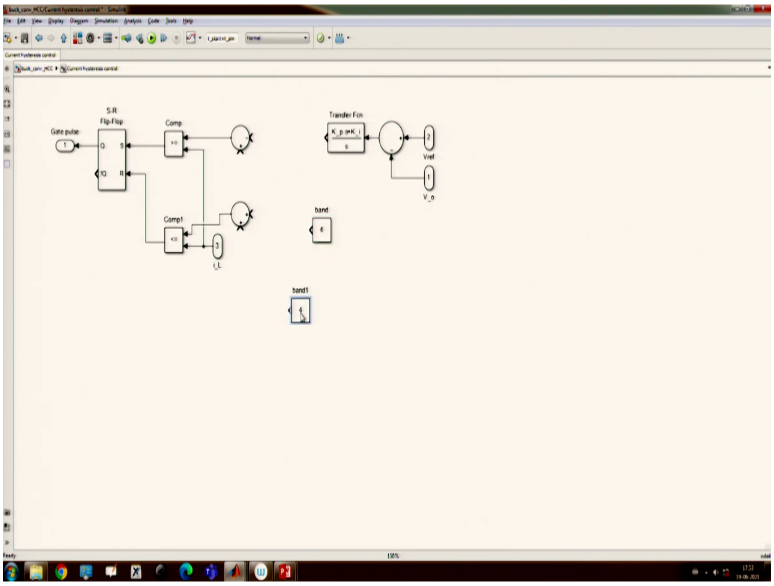

So, this is my 20 Ampere, ok. So, this is 20 Ampere, this is also 20 Ampere.

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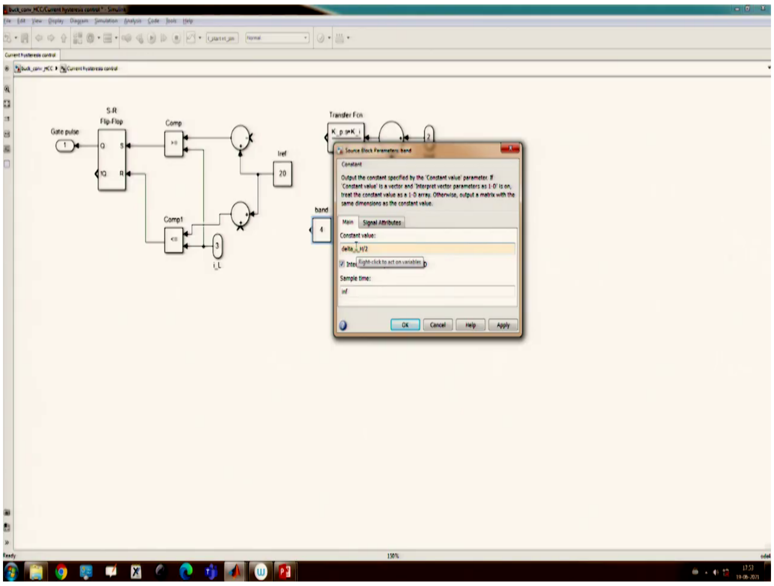

What do we want to add? I want to add delta I H by 2.

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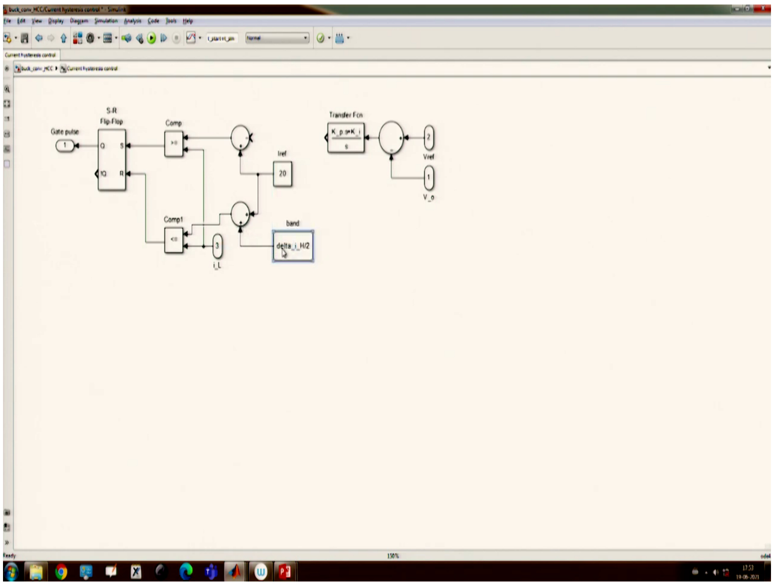

I will recall that delta H by 2. I want to add here and here the same thing, I want to subtract one; we are adding, and another we are subtracting, ok.

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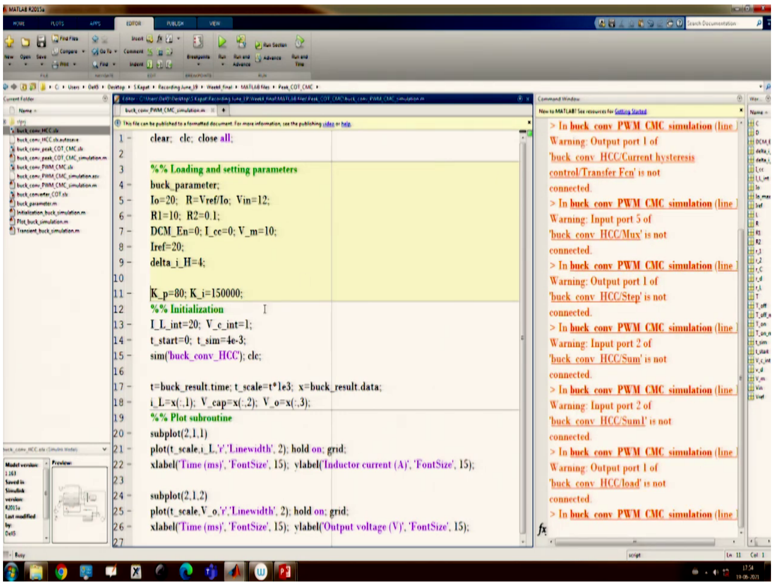

Now, let us go back and we will say 20 Ampere current. So, I ref that means this is my 20 Ampere, ok. And what we took here is a delta i L So, we will copy paste here. Let us say a 4 Ampere, ok. So, here we are not using any closed loop control. So, we can simply disable this block, and let us run and see what happens, ok, because it is there in the loop. So, we want to see that can we get, ok.

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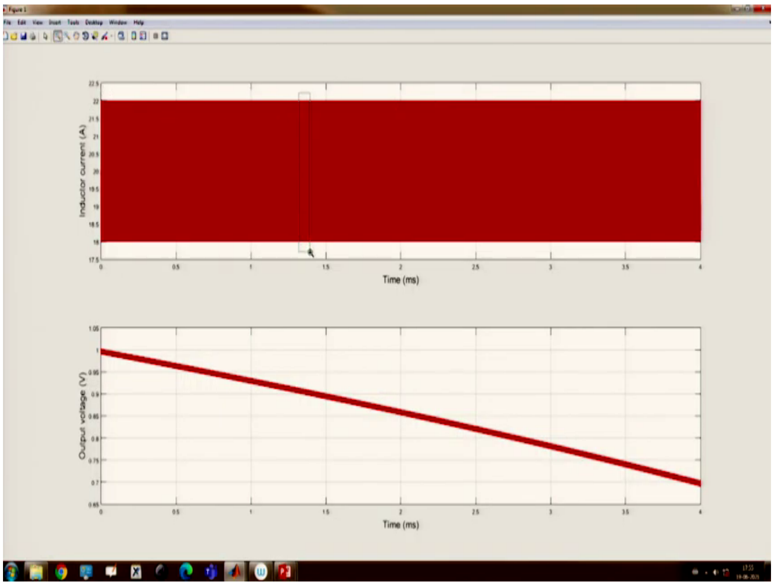

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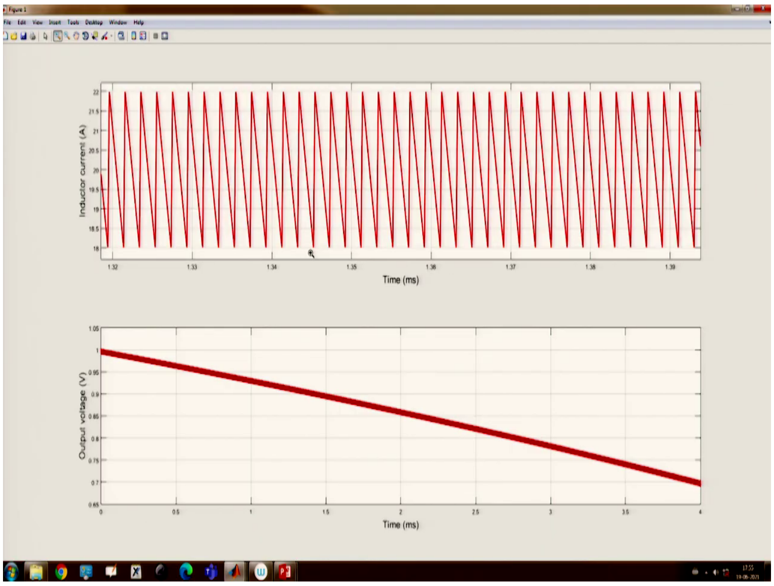

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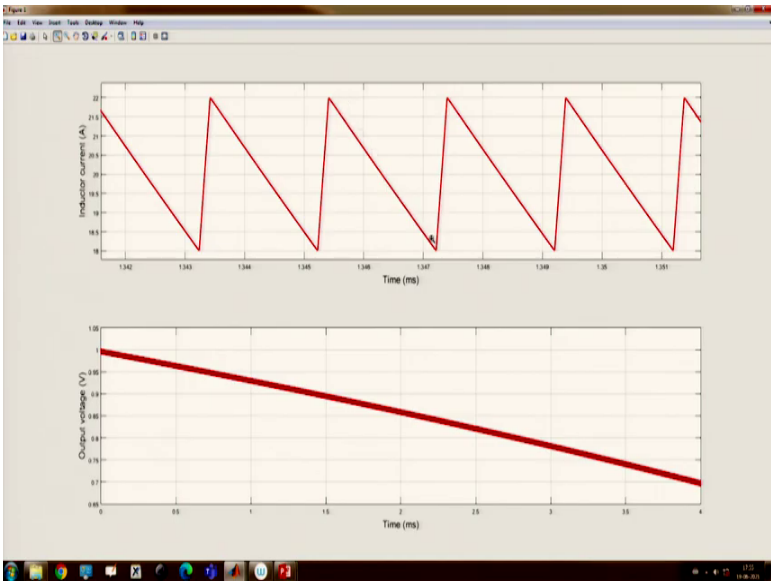

So, you can see in this waveform that we are trying, we are getting a current in between 18 Ampere to 22 Ampere. My average is 20 it is perfect. But there is no regulation in the voltage because we left the voltage open.

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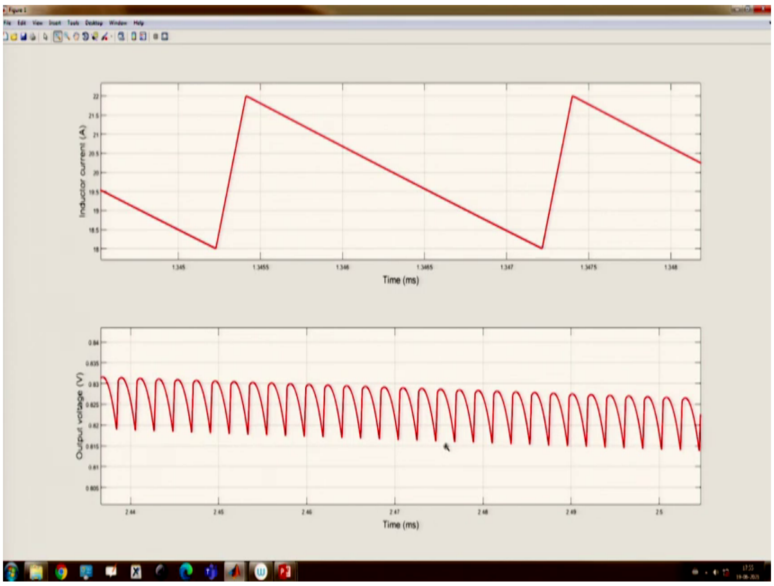

Though, we have applied 20 Ampere load current, but because due to the drop the balance you know average inductor current if you set 20 Ampere, and we expect the average voltage to be you know because the same average current is going out as a load. So, the voltage is depends on the charge balance, in the overall cycle balance. So, that is why we do not have any control over the voltage, but we can add the closed voltage loop, ok.

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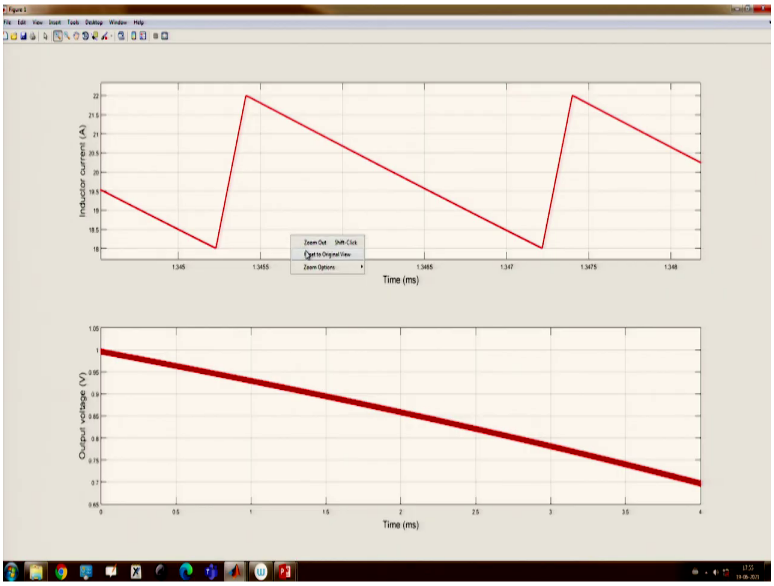

Now, if we want to regulate the output voltage at the same time. So, what modification we want to do? Now, the peak reference; that means, this 20 Ampere which is a reference that I will take it from the closed loop, that reference I will take it from the closed loop because that is the reference now.

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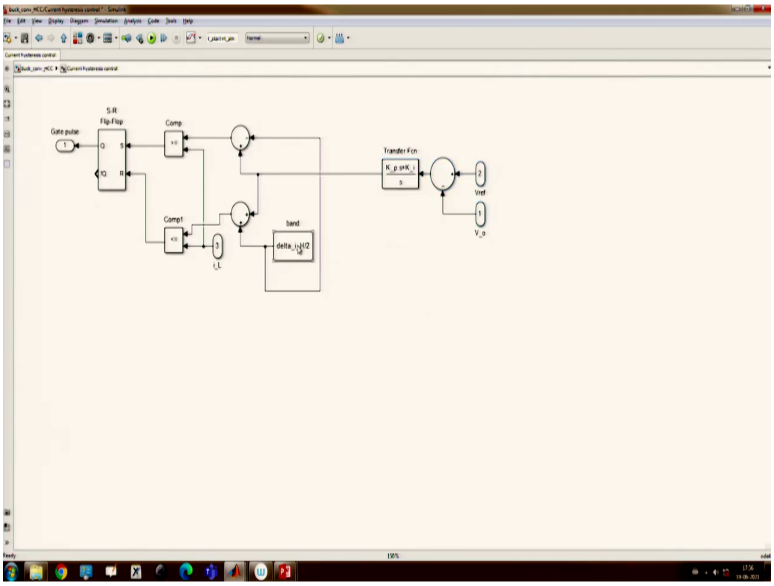

The other things are all same. That means, I will tell you what exactly I am doing, ok, running for let us set 2 millisecond, ok.

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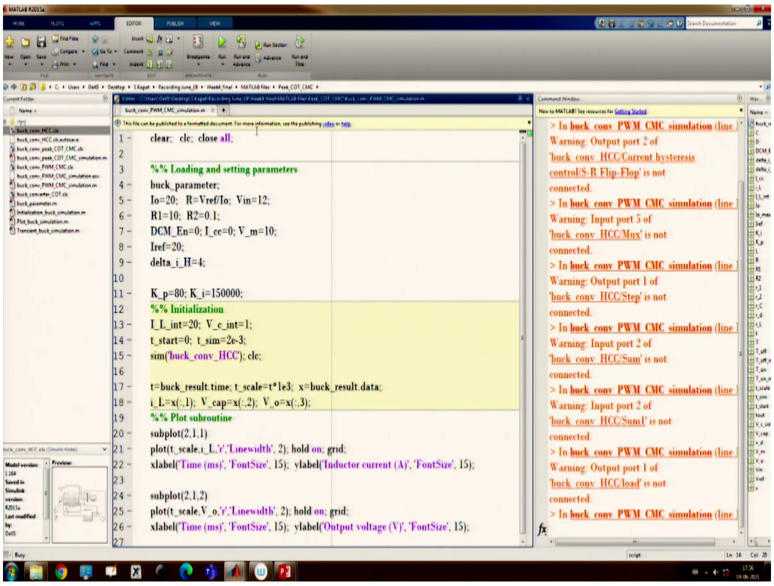

Here, what I am doing?

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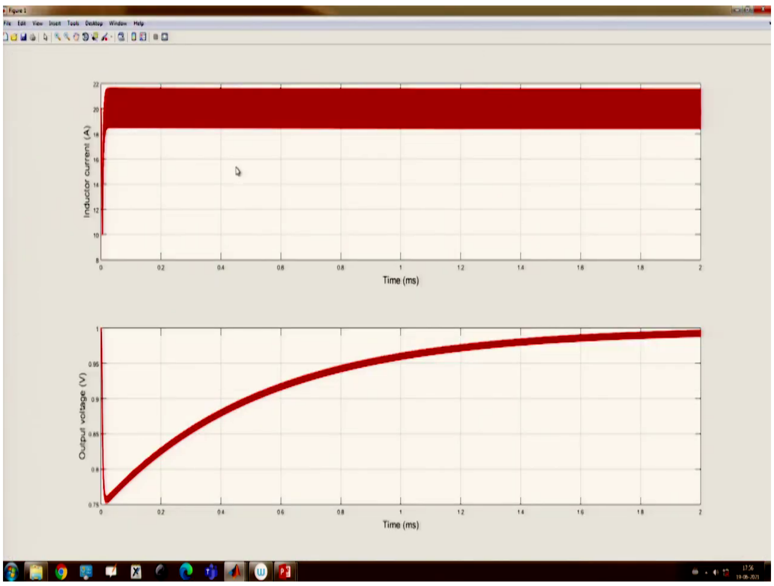

Earlier, we set, now you see we are getting few things we need to observe. The first thing though we are now getting closed to the regulated voltage; that means, 1 volt is nearly coming to the 1 volt, but we set 4 Ampere voltage threshold limit.

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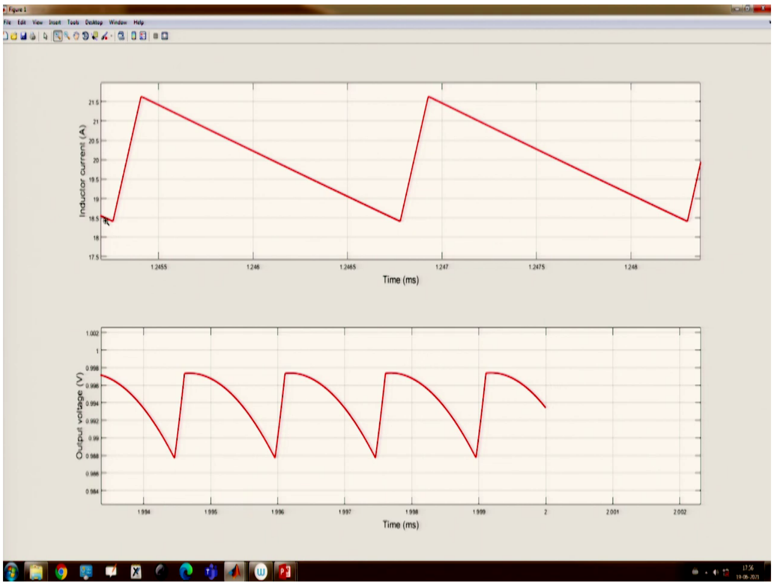

That means, if we check this 12 point, 21.5 and 18.5 close to that, but it is coming only 3. That means, though I initially when we set you know what I am comparing, let us keep a hold it, I will just hold this value.

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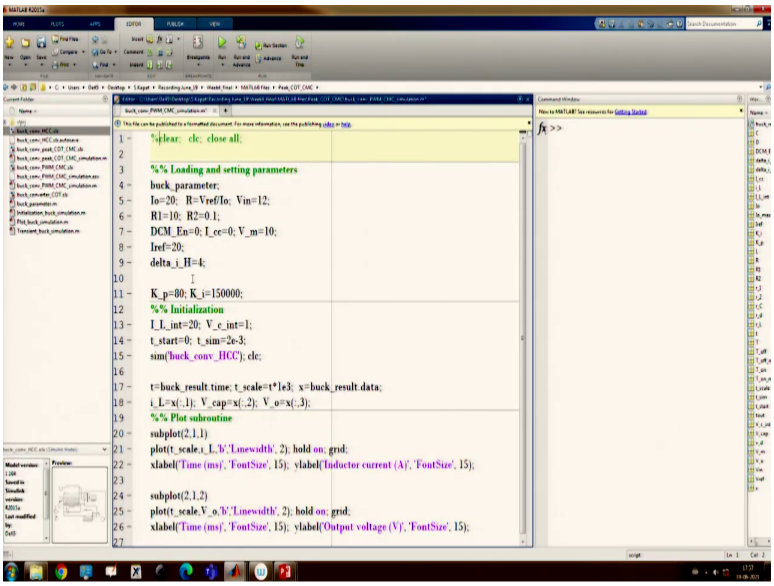

The one case we are closing the outer loop and another case we are not closing the outer loop, ok.

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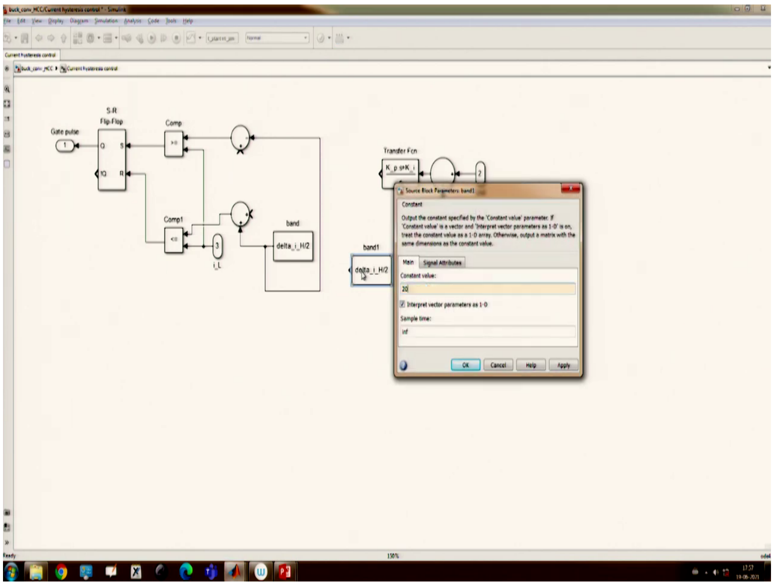

And what we are doing here, we again open the outer loop and what we set was 20 Ampere is a reference, that we will set it here.

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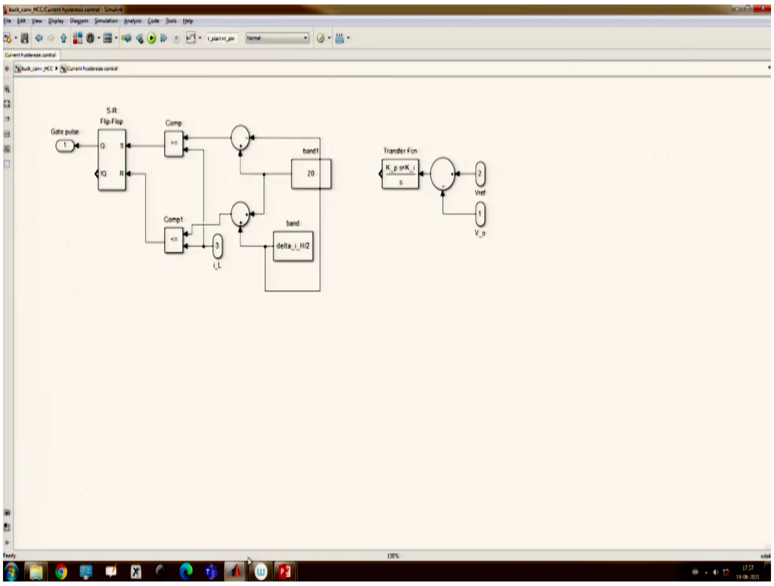

So, in one case we are using a fix reference and see I want to show what actually happened.

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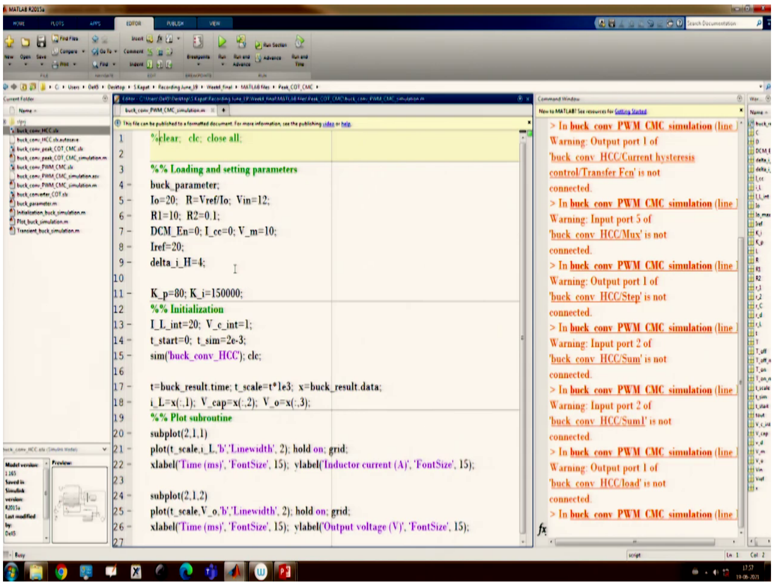

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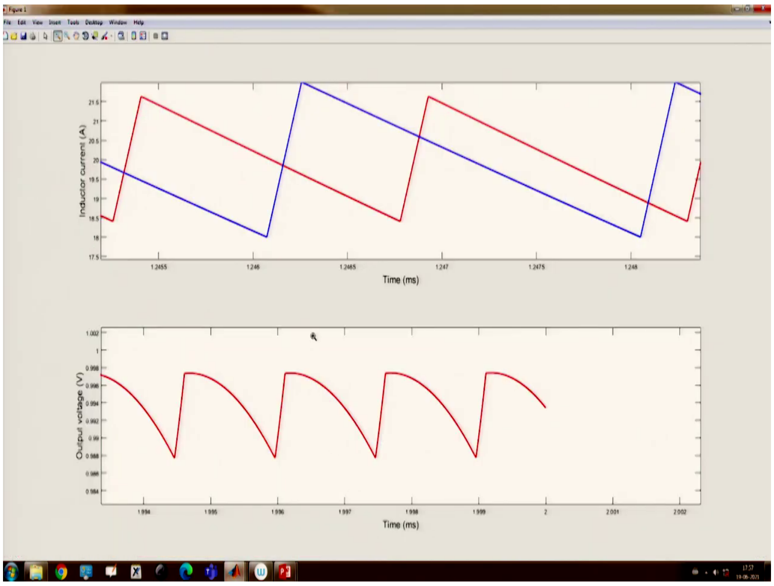

So, two thing we can see here. We can notice here.

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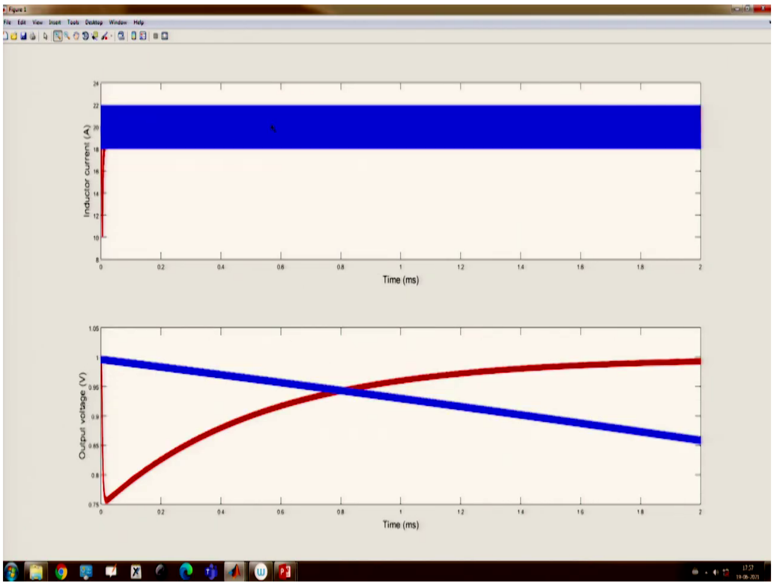

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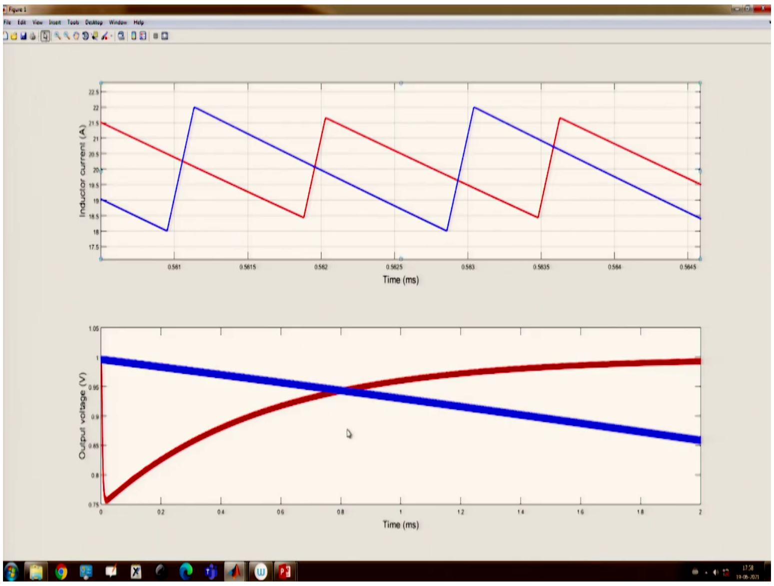

The first thing you will notice that when it was running under open loop. And if we greed it, the current is perfectly maintained between 18 to 22 that was our desired value. That means we want a 4 Ampere current ripple and the average should be 20. Everything is fine. But the voltage was not regulated.

But, if we want to regulate the output voltage, we close the loop, then we found the voltage is getting regulated here; that means it is getting regulated here, it is getting regulated here, the red one. But the current is no longer 4 Ampere. Though we set 4 Ampere hysteresis band, but is no; that means, there is something which is causing some actual inductor, current ripple is not exactly the same as the desired one.

And there are research papers which show that this is because of the output voltage ripple effect. Now, if we make the ESR to be 0, I will show you under the closed loop.

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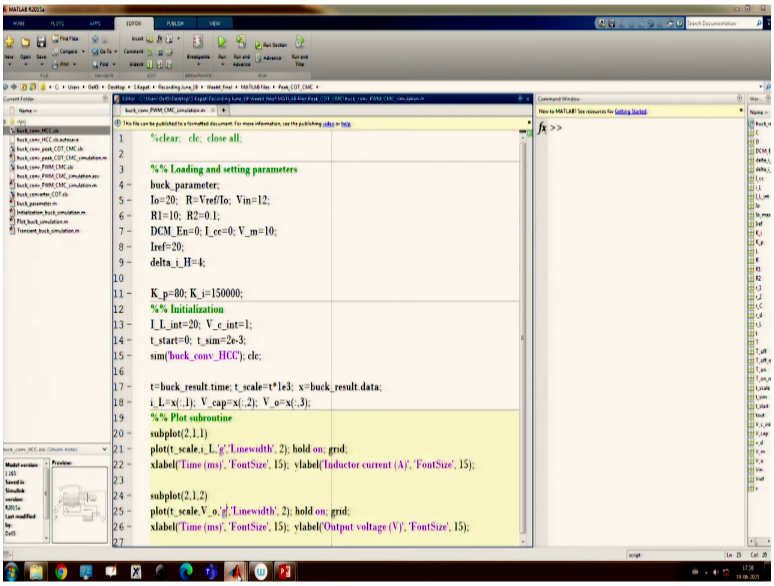

Now, we are doing closed loop and I am using a green color. Again I am using a closed loop, ok. And let us go.

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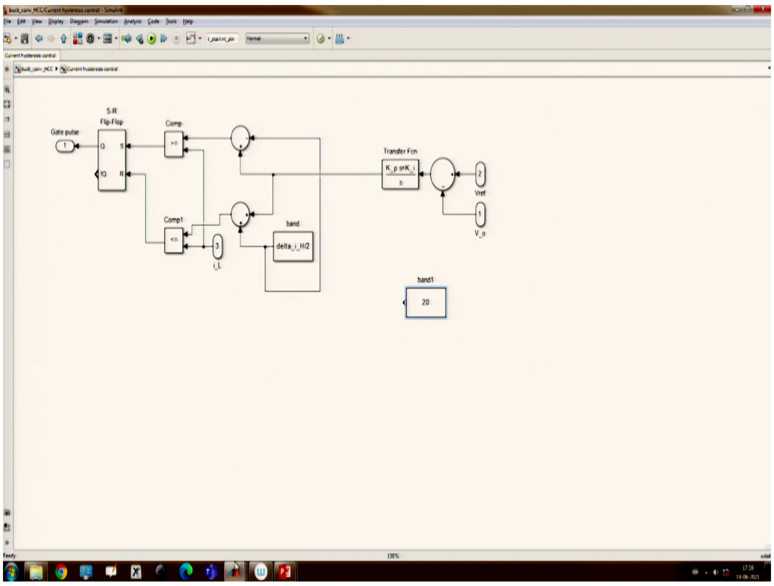

And I am breaking this loop and using a closed loop. That means I am just moving it. Now, it is a closed loop.

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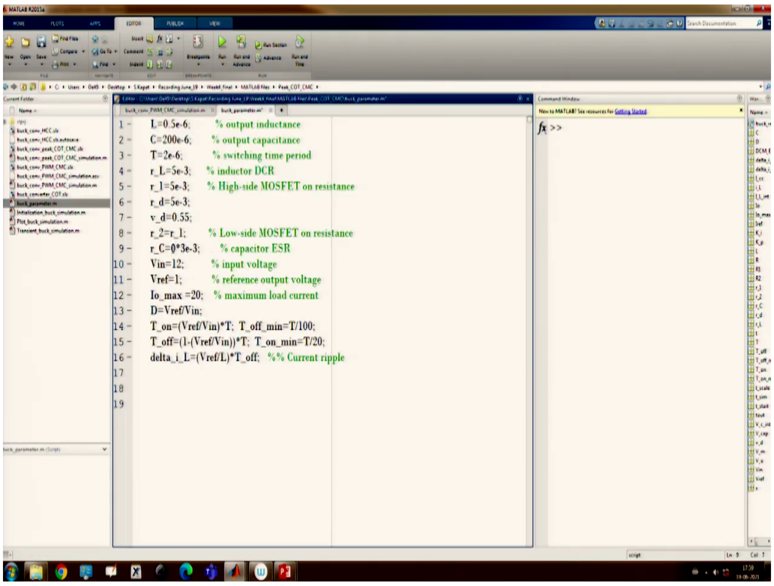

But, we are making some changes in the power parameter where we are considering ESR to be 0. And I want to show you what happens if we run this simulation.

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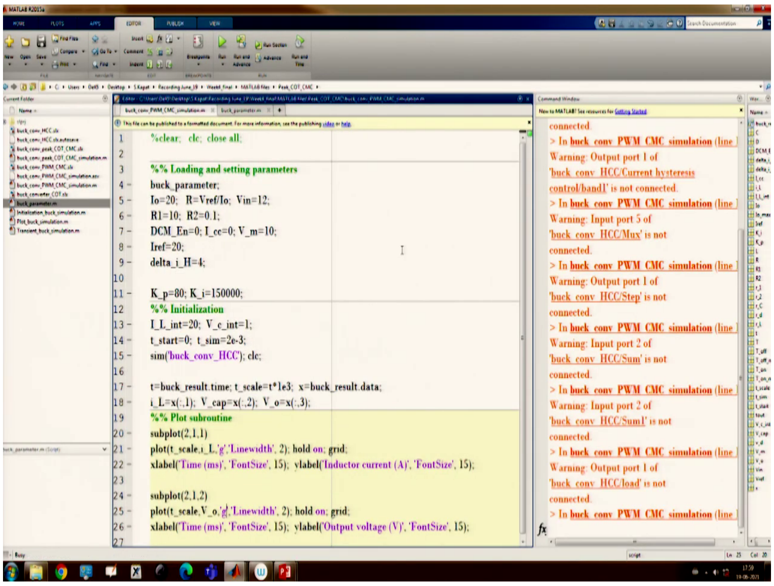

Now, it is under closed loop, ok.

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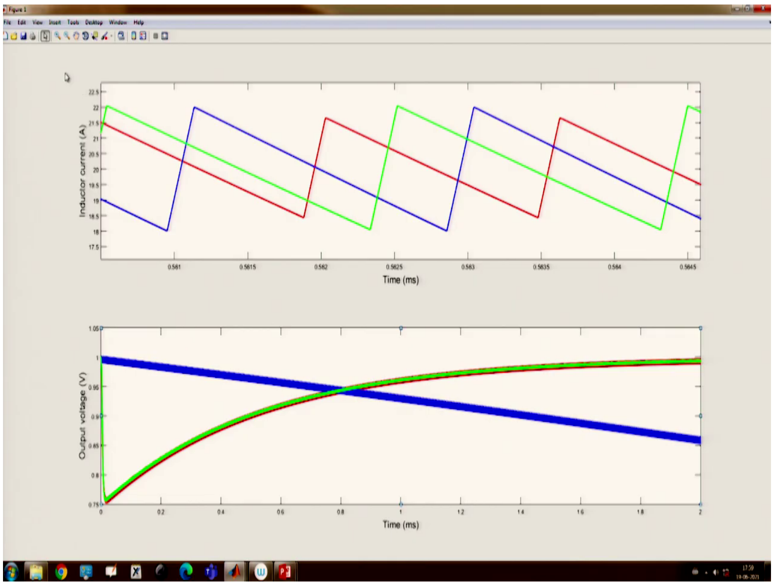

Now, we want to see what happened, right?

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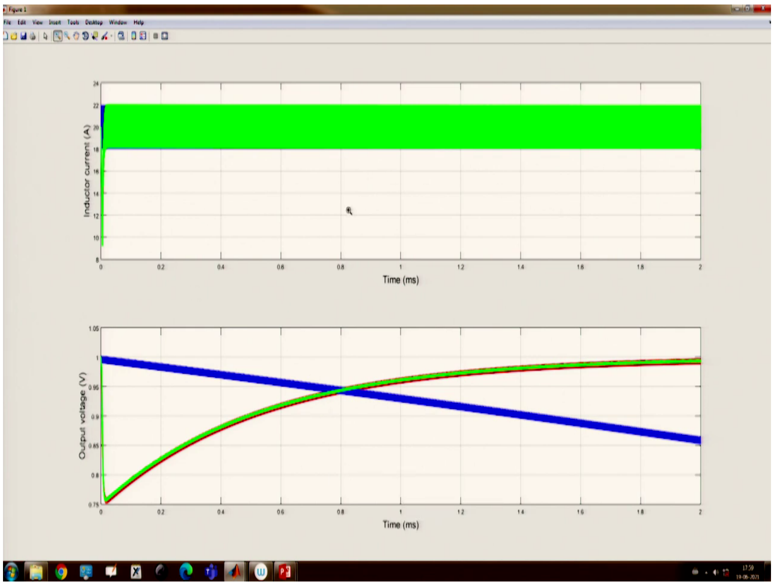

Now, you will see very interestingly that, if we take you know particularly, let us say this point now, the green color is almost achieving 4 Ampere current ripple.

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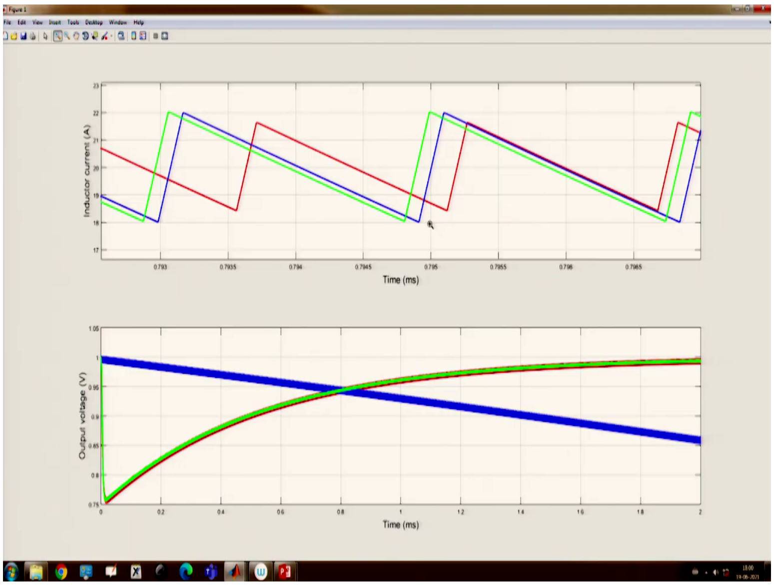

That means the inductor current ripple is more or less same as the hysteresis band. And also, the output voltage is getting regulated for the green waveform.

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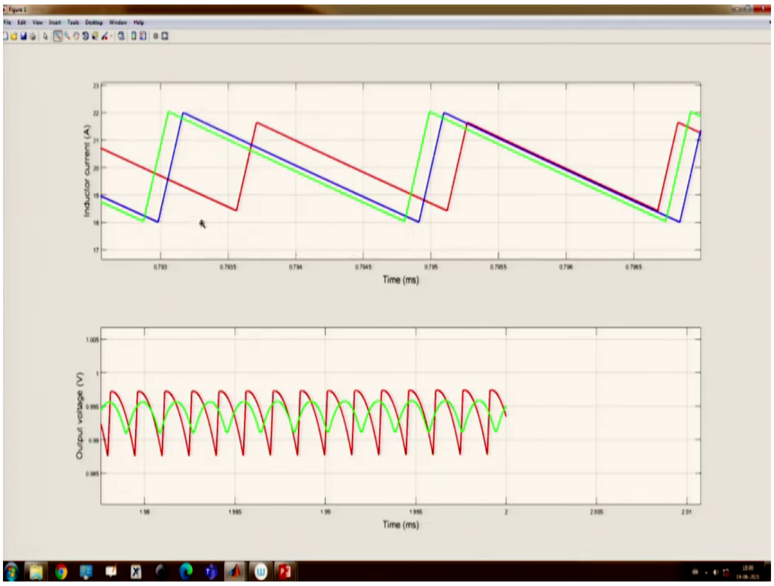

That means there are 3 things. The first thing, the blue one, is the outer loop opened only current loop closed; that means, we have setting. But there was no regulation in the output voltage that we found. That means, you know I am just comparing 3, and if I take the final few cycles, that means, close to 2, I am just taking final few cycles, that means here.

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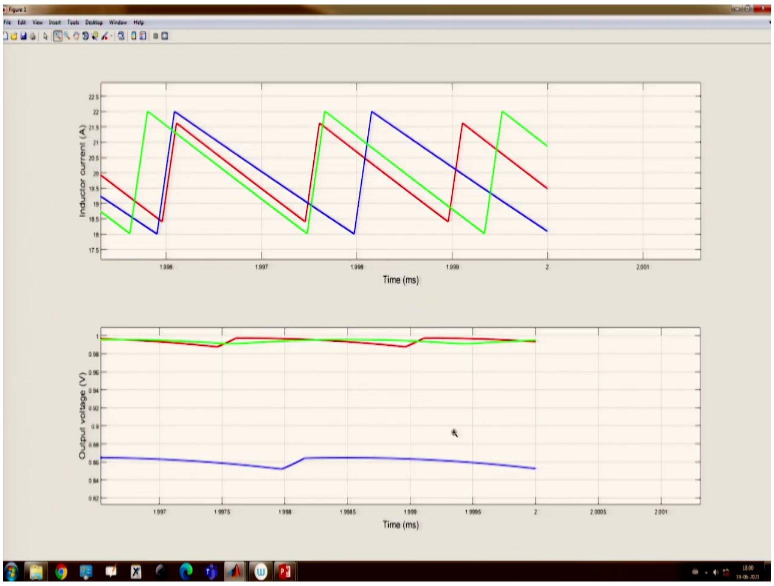

So, what are the observations? That means, the first one is the green one, where it is under open loop and we are making sure the current track perfectly between 18 to 22 Ampere and that is exactly happening. But there is no regulation in the output voltage.

Second, we now set. We close the loop and this is a red color. Though we set 4 Ampere hysteresis band, but we are not achieving, we are getting less. And the third case is the green color where we remove the ESR. And it is under closed loop, and we are getting close.

That means the hysteresis control. If we close the loop, that ripple has a direct impact on the actual current ripple and the hysteresis band. And this has been while reported in the literature, it is sensitive.

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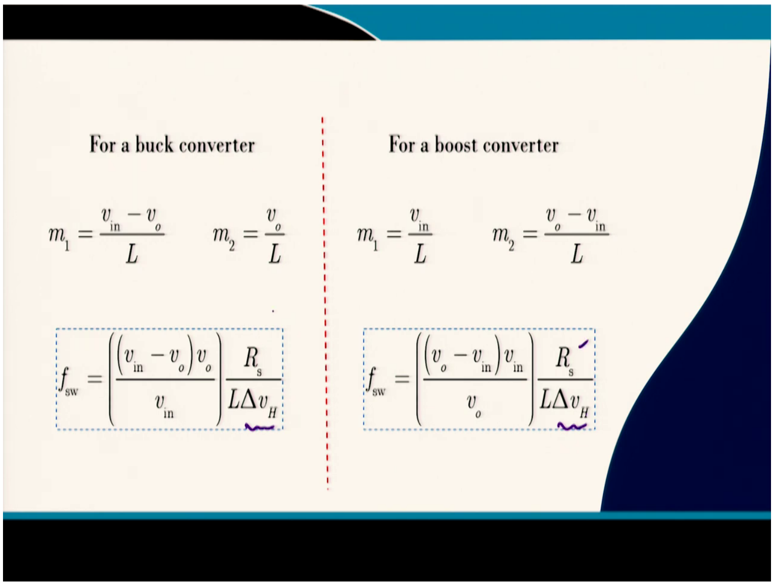

So, but in generally in buck converter, the switching frequency is you know proportional, inversely proportional for to the hysteresis magnitude and also depends on the sense resistance and so on.

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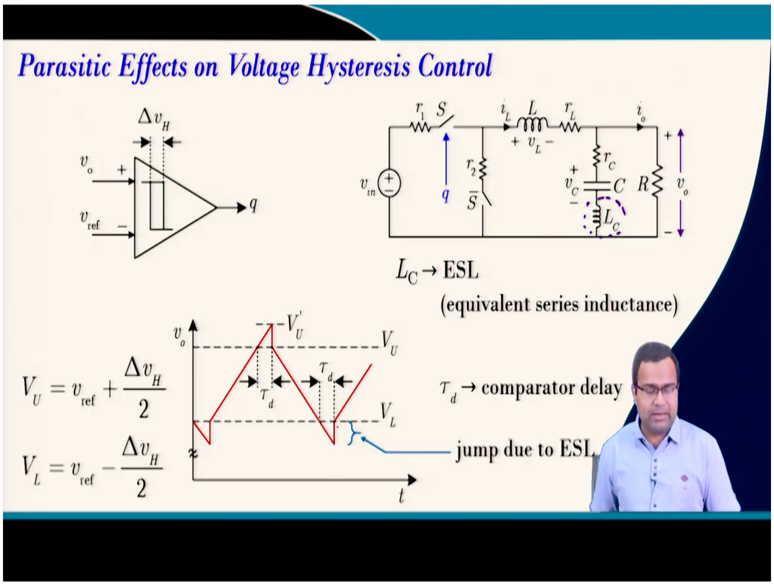

So, the parasitic effect of hysteresis control, if we take purely voltage hysteresis control, then if there is any parasitic ESL, Effective Series Inductance that can introduce some jump, and that can cause some problem in hysteresis controls. You have to be very careful in terms of layout and other stuff, if you want to go directly by voltage base hysteresis control, output voltage.

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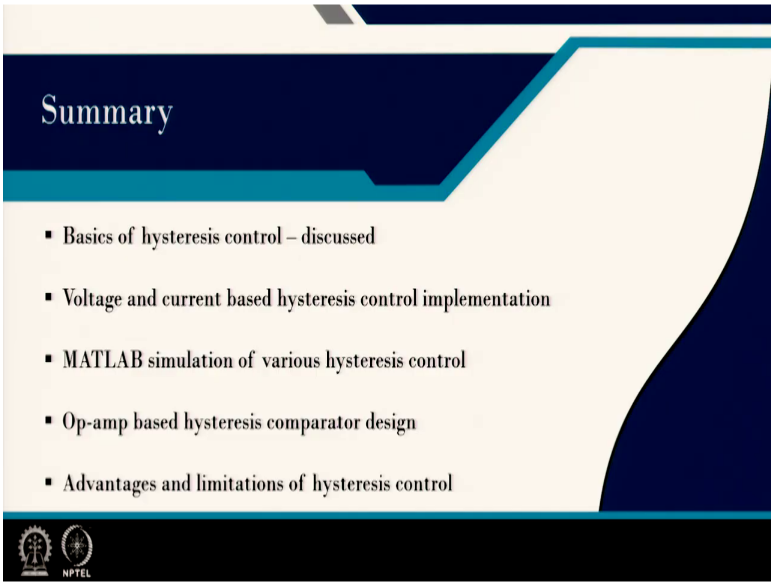

So, that means, we have discuss the basic of hysteresis control; we discuss voltage and current based hysteresis control and implementation, MATLAB simulation also we have shown, op amp based hysteresis comparator design we have shown, an advantage and limitation of hysteresis control are also discussed.

So, with this I would like to conclude this session.

Thank you very much.