Digital Control in Switched Mode Power Converters and FPGA-based Prototyping
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Module - 03
MATLAB Custom Model Development under Digital Control
Lecture - 30
MATLAB Model Development for Digital Current Hysteresis Control

Welcome, so in this lecture, we are going to talk about MATLAB Model Development for Digital Hysteresis Current Control.

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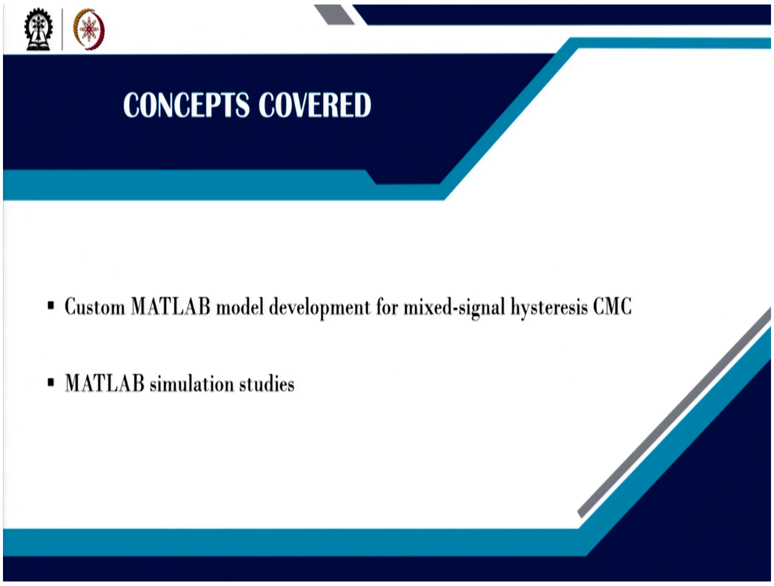

So, here we will first you know talk about Custom MATLAB model development for mixed-signal hysteresis current mode control and then we will consider a few MATLAB simulation case studies.

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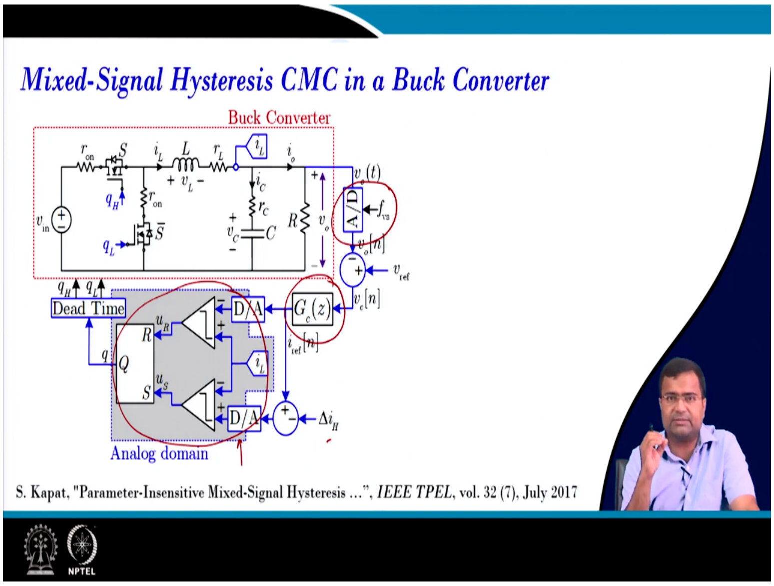

So, first, we will recall our Mixed Signal Hysteresis Current Mode Control in a Buck Converter that we discussed the last week. So, this is the generic representation where you know you need to have one A to D converter for the voltage loop in digital and then this is the compensator.

So, typically we take a pi controller then you need to have a D to A converter. So, we can use a single DAC or you can use 2 DAC. So, this is for basic conceptual realization and the inductor current in analog. So, this is the whole block in the analog domain and so you know we have discussed it in detail, but this can be realized using 1 DAC as well as one comparator and that has been discussed in this paper.

Now, this is the hysteresis band which is in the digital domain. So, we can customize this band to regulate the switching frequency.

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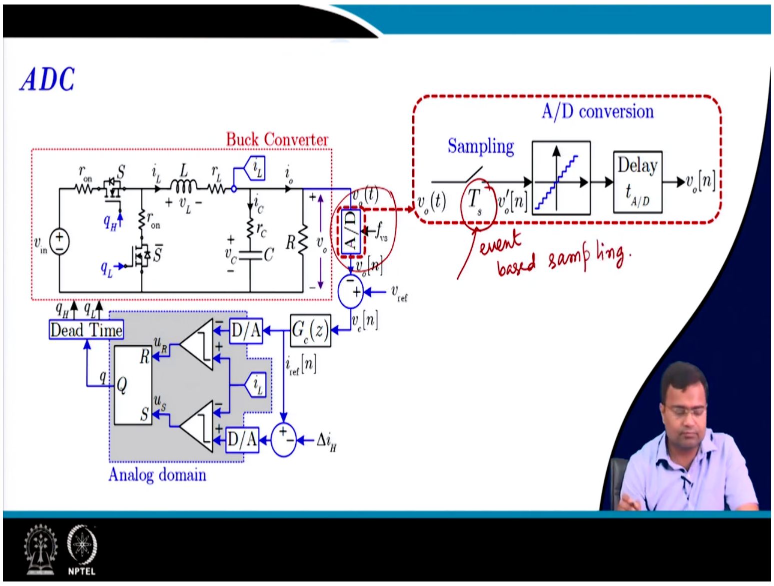

If we talk about this approach, so first we need to have ADC. This ADC is a sample non-uniformly; that means, where are you going to sample? So, you can have if you go for a peak current mode version, then we can sample the voltage at the valley point. If you go for a valley approach then you can sample at the peak or we can take the sample 2 times peak and valley.

But here we are discussing we are sampling once per switching cycle. Now this ADC we need a sampler quantizer and delay and here it is not T s. So, it should be an event-based clock, because even if you use a uniform sampling it will lead to multiple limit cycle oscillation. So, it should be an event-based sampling approach.

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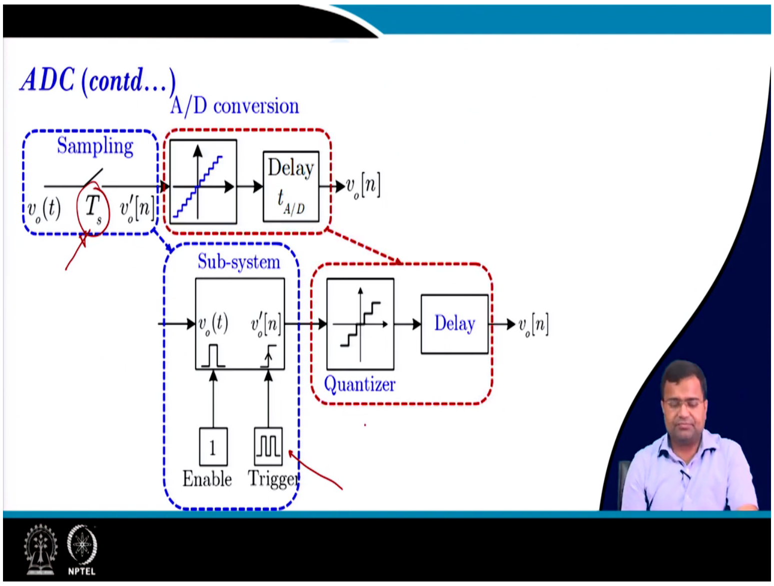

So that means, this event we will create. So, here we are not talking about it as a general representation of ADC, but this T s here is a sampling time that is going to vary. That means, if based on the a, I will not fix the time, but I will fix the event and that event will be created by this trigger pulse. Then we need can consider a quantizer and delay ok.

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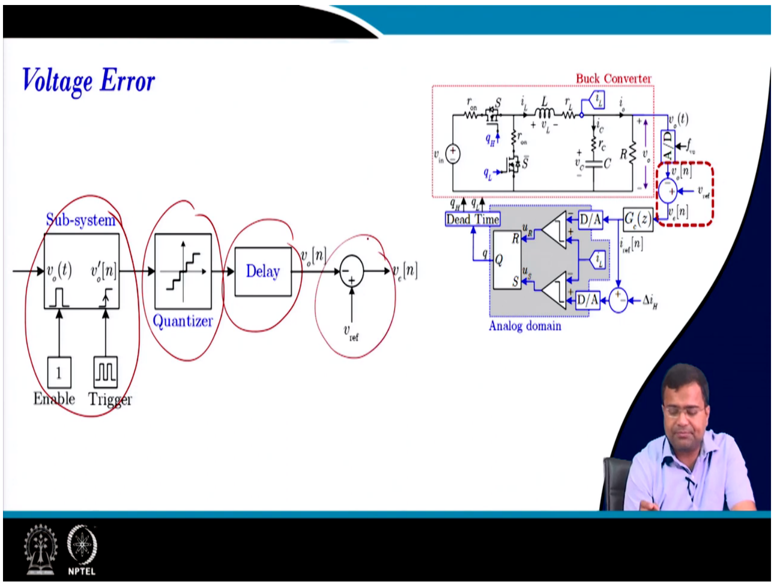

So, in this MATLAB realization, we want to make it simple, with no delay no quantization it is just how to realize event-based sampling and how to realize the mixed signal hysteresis current control. Now, after this ADC then followed by the quantizer is the generic realization.

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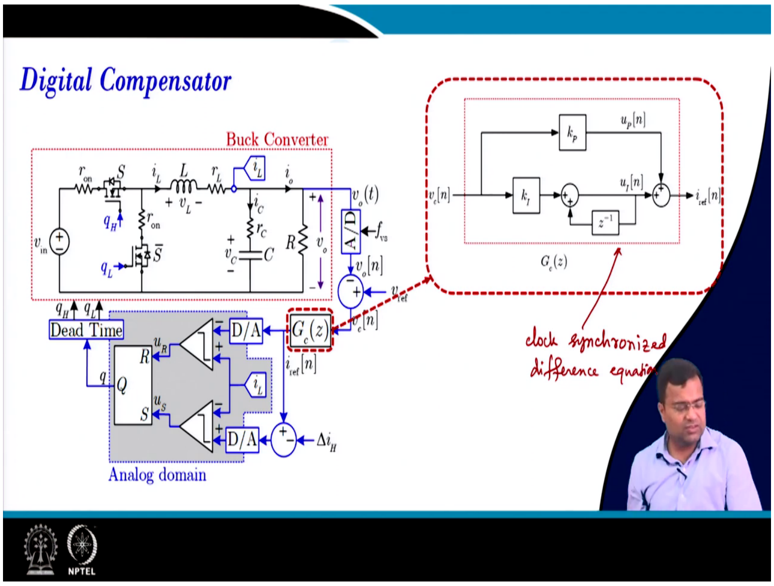

Then delay you can have an error block, then after this error block we can have a controller. So, if you take a pi controller and we have discussed that this controller has to be realized by a difference equation. So, it is a clock-synchronized difference equation ok.

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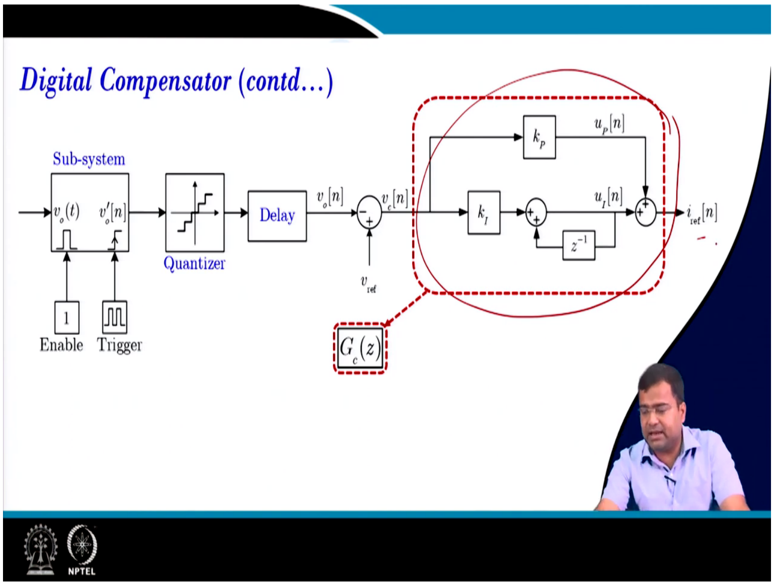

Next, that means, if we realize this pi controller I will go to MATLAB and show the next part that you will generate the reference current, and since we are using Matlab, but typically this is digital we need to add D to A converter.

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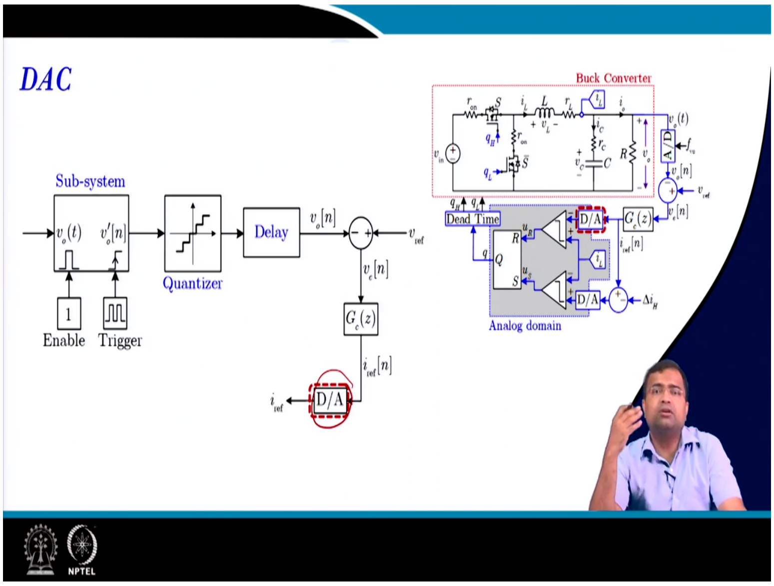

So, DAC in DAC in MATLAB you can simply use a scaling function, but in actual realization, you need to consider a D-to-A converter. Then after this DAC, we have to decide what technique are you considering are you going to use a peak current-based approach, valley current-based approach, or average current-based approach?

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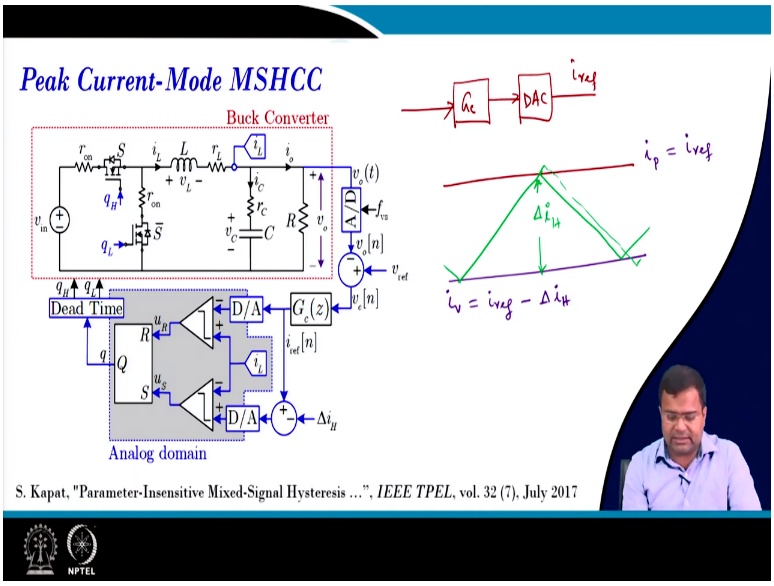

So, if we go for Peak Current-based approach then the reference current; that means, whatever reference is coming I am saying that the output of the controller is followed by DAC, this is my reference current ok.

So, if we take this reference current when we say we are talking about the peak. So, this is my peak current which is set to the reference current and my valley current is simply i ref minus delta i H, because let me write here sorry. So, my i valley this is my i valley which I am writing i ref minus delta i H and I want to keep the inductor current within this band ok.

So, here it is peak means. The controller output is directly controlling the peak current. If we want to use let us say a fixed current difference; that means, a constant current difference command, so inductor current will just track it on the peak value detection.

As we have discussed in the last week since we are doing event-based sampling, the hysteresis band and the actual current ripple will be identical in this case. Because even though there is a ripple effect in the output voltage that will be discarded because of event sampling and under steady state there is no ripple effect.

So, your current hysteresis band and the actual analog current are the same, provided that you do not consider any propagation delay. In case of a delay, you can get some additional current here because of the delay. So that means, your actual current ripple can be slightly higher than the reference band due to the delay comparator delay and another thing. But in general, if you take the ideal case to start with you can keep the current ripple and the hysteresis band the same. So, this is also discussed here.

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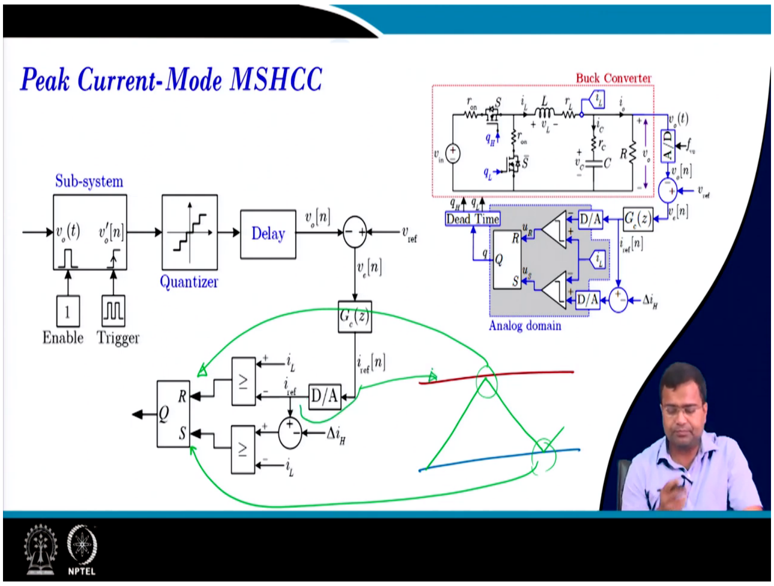

Now, in MATLAB I mean actual realization as I said reference you directly set as the peak value. Whenever that means, this is current; whenever the inductor current hit the peak then you reset that is why it is reset and whenever it hit that means, the inductor current hit the valley then you again set it. That means if I draw neatly; that means, let me draw this one and green. So, here it will reset and here it will set ok, and here we are using reference. So, the reference is directly keeping the DAC output.

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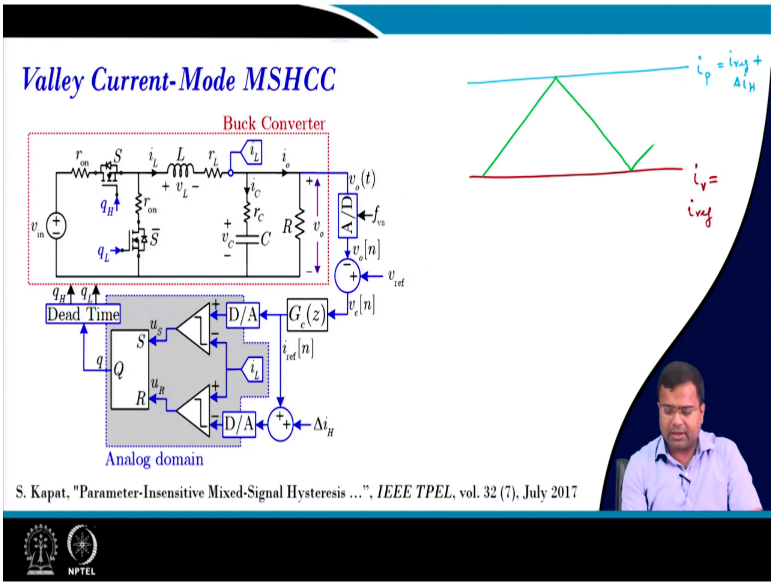

Now, if you do valley? That means, we will directly use this reference current; that means, we will directly use the reference current, this is my i valley is set to i ref an inductor current, and that means the peak current will be here IP. And what will be IP? It is nothing but i ref plus delta it and your inductor current will be simply within this band. So, you can realize this using this algorithm and we can adjust the hysteresis band.

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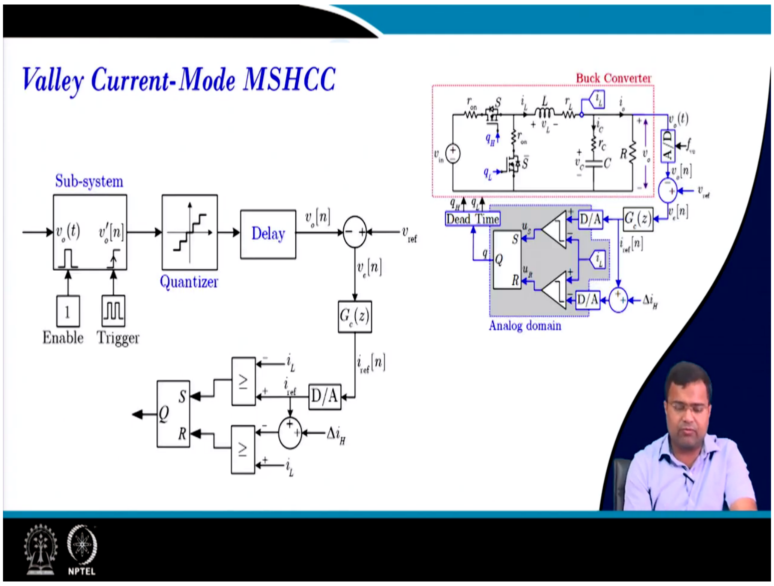

Now we can realize using Simulink I am going to show the peak current, but you can do valley as well as average.

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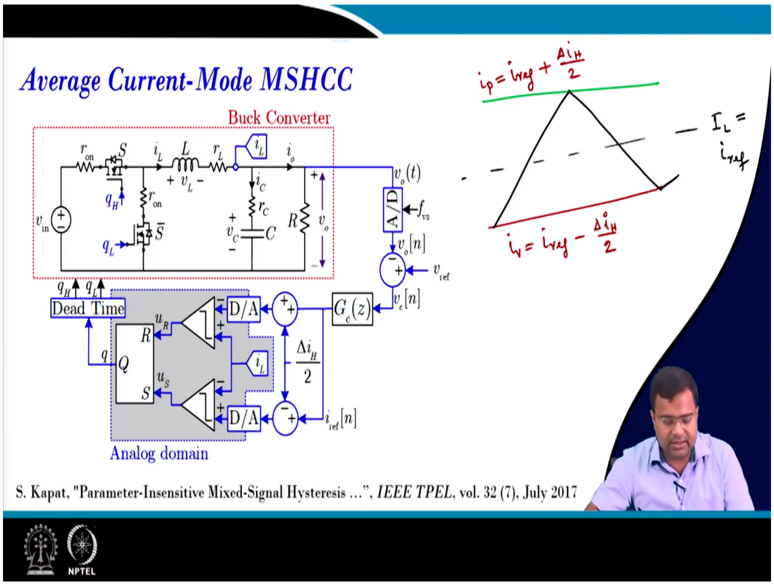

What will be the average? In the case of average that means if I take this peak and valley; that means, this is my peak is i ref which is the controller output plus delta iH by 2 and my valley is nothing but i ref minus delta iH by 2 and then we will keep simply within this.

So that means, we can precisely control the inductor's current average value and this is you can set it as equal to your set value, which means we can maintain it. the average value of the inductor current we can keep perfect track of the reference current if the current loop is stable; that means if it repeats under a steady state.

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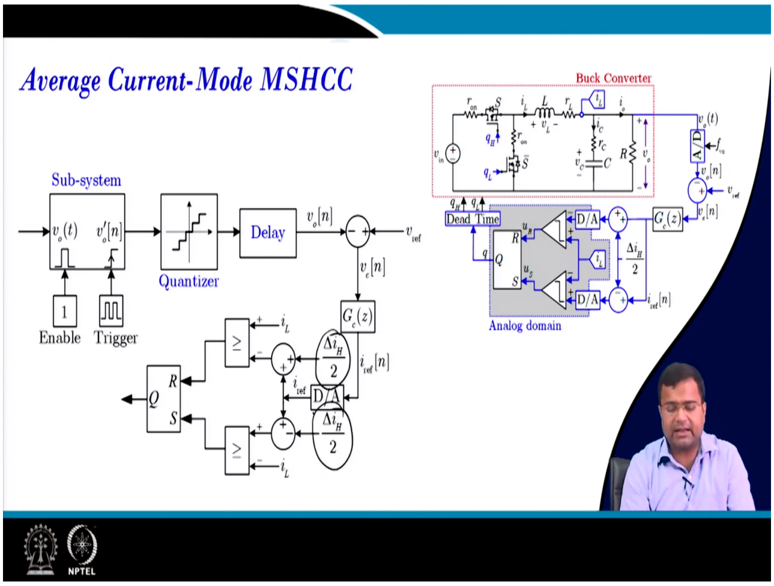

And we can implement this by using you know the reference current given by adding delta H by 2 and subtracting delta H by 2.

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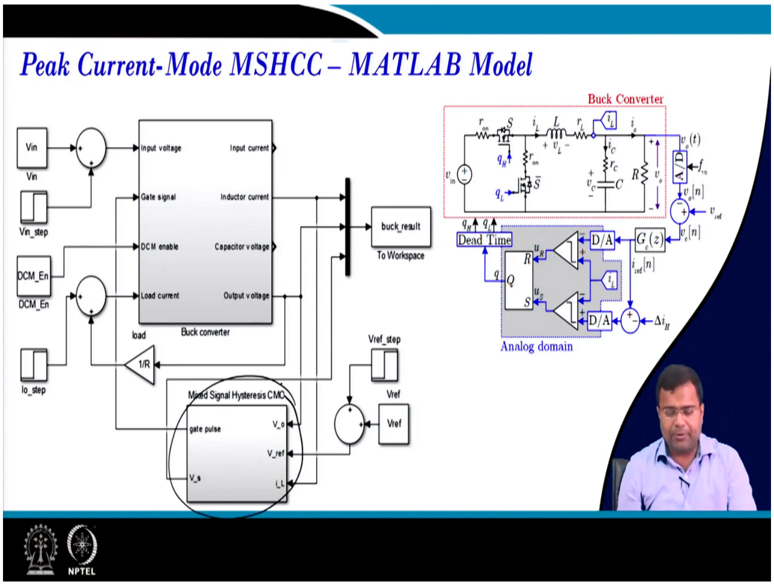

So, this is the overall MATLAB block diagram that I am going to show.

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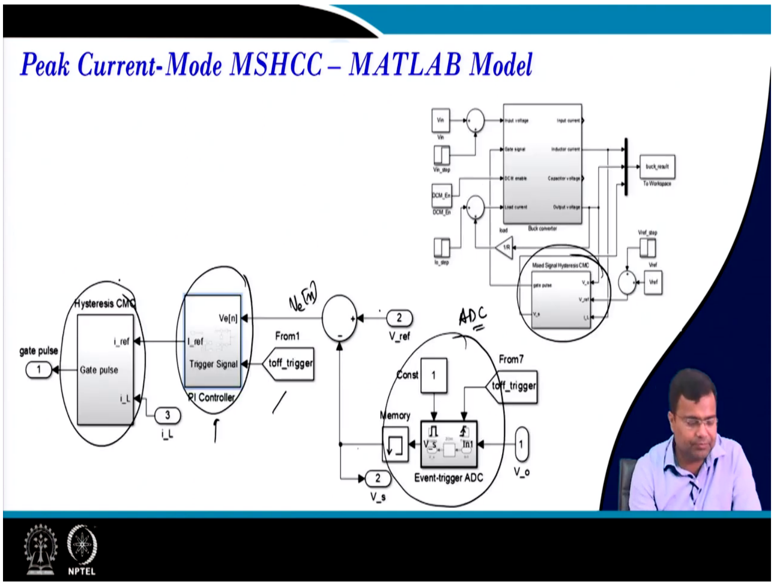

And if you go inside this block; that means, if inside first you will have an event trigger ADC. So, this is the ADC for the voltage loop which is the event trigger, then you will generate the sample voltage then which is compared with the reference voltage this is my error voltage and this error voltage goes to the pi controller this realization is the same as our earlier realization. But only the trigger clock will be different because it is a clock-synchronized difference equation.

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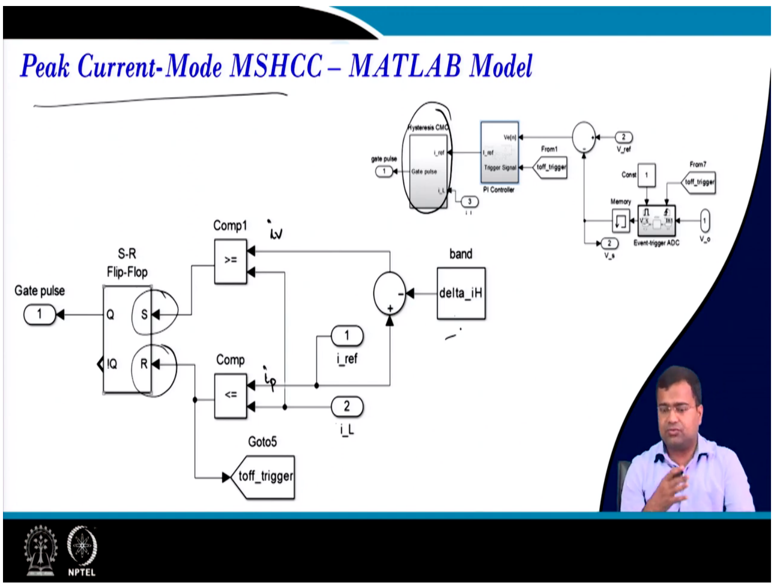

And if you go inside the hysteresis block I am talking about this hysteresis block; that means if you go to this hysteresis block what is that it is the same as analog hysteresis control and where we need to set delta H. And here we are using the peak base peak current base; that means, peak current mode control. So, the reference current is directly compared with the inductor current to generate the reset pulse and the valley current. So, this one is our peak current and this one is our valley current.

When the current reaches the valley current the switch is turned on. So, it is a set pulse and this is a delta H we can adjust to achieve the desired switching frequency.

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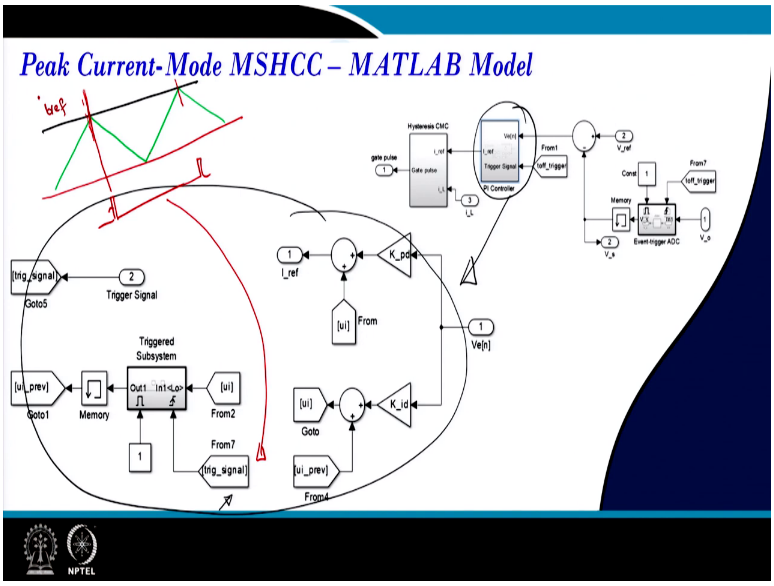

And the output voltage realization sorry controller pi controller this is what we have been discussing for many classes. So that means a clock synchronized difference equation where the trigger signal is different and we are going to MATLAB to see.

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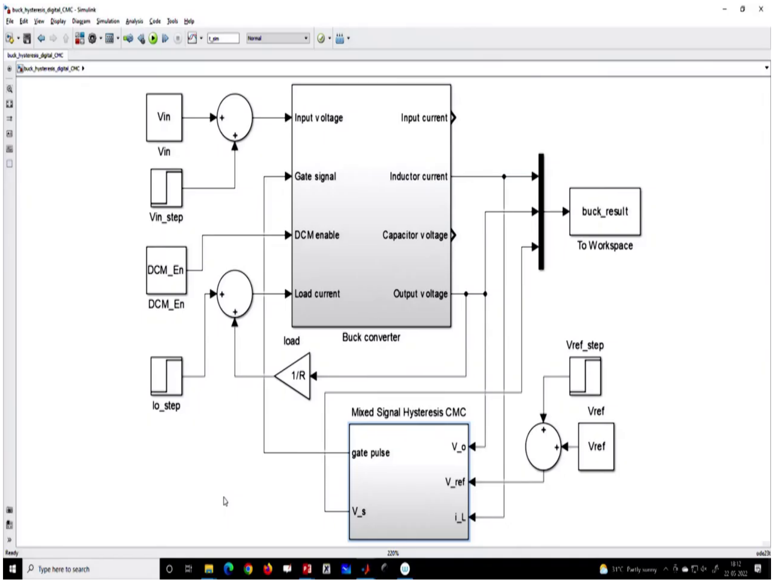

What is the Trigger signal? So, this is the Mixed Signal Hysteresis block.

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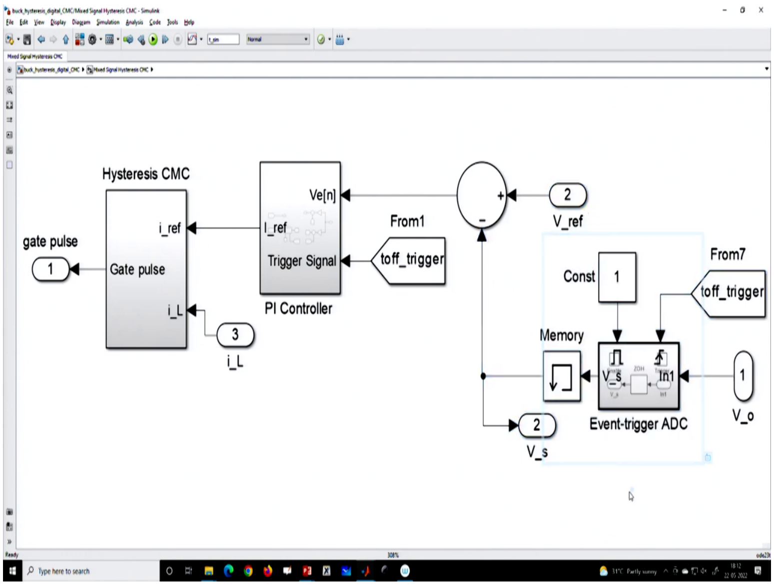

If you go inside we have discussed this is my event trigger ADC.

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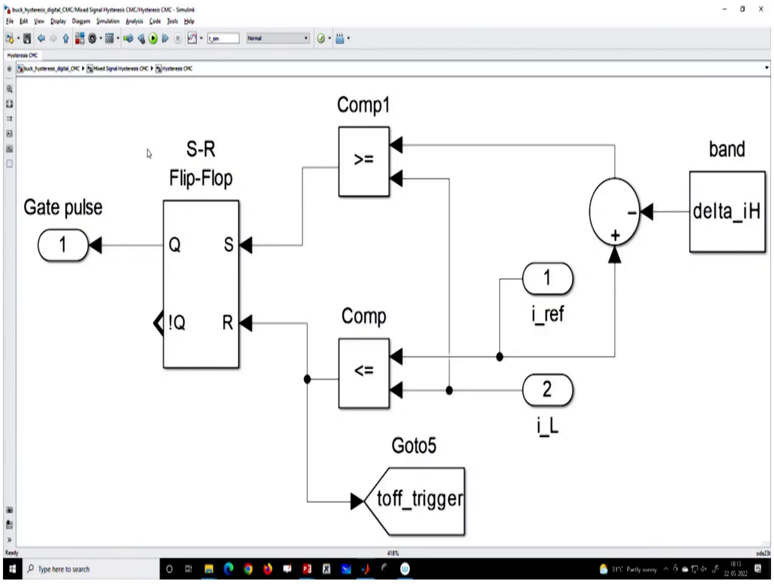

Then this is my hysteresis block that also we have discussed. And now the event we are creating is the peak; that means, whenever the inductor current hit the peak current that time we are sampling the ADC so that we can update. So, here the sampling point is selected as the trigger point; that means if we go to our realization if we consider this is my peak current reference sorry. If we consider our peak current reference to be if this is our i ref and if you use the inductor current where we have a valley here.

So, this is the point we are taking sorry this is the point this is the clock. So, this clock is ours, this event trigger clock ok. So, we can select this clock also, but you know there are other aspects of stability, but I think you can. You can also delay by one sample, but you will also get some impact in terms of transient performance. So that means, here we are using this event clock.

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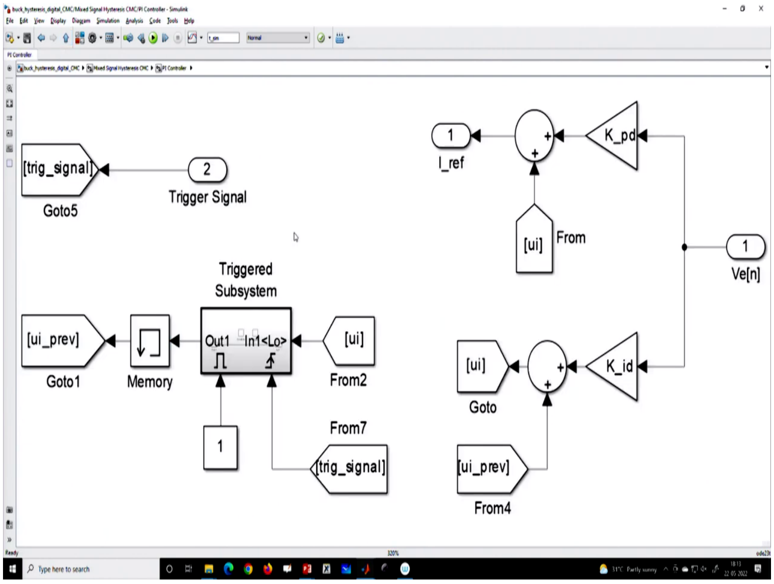

And this event clock is used to realize this and we have discussed it multiple times. So, I am not going to spend time on that. So, you want to run a few simulation case studies.

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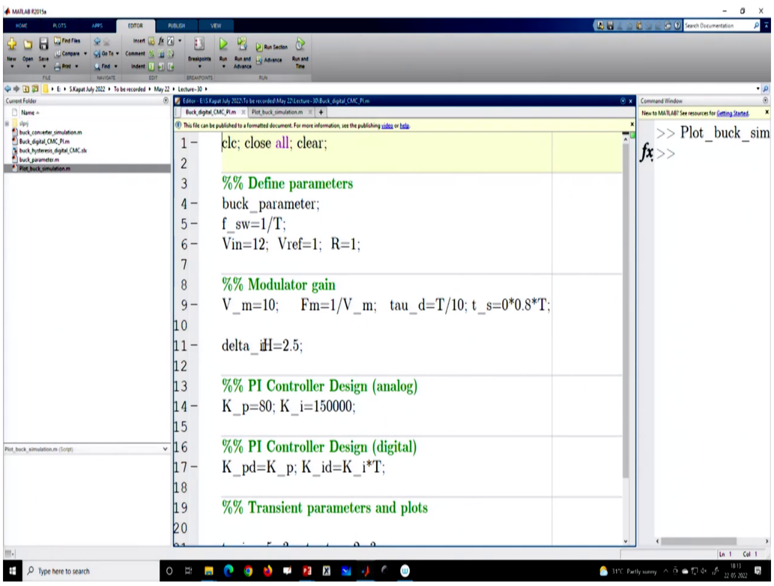

That means, we want to show that hysteresis control will never become unstable for a wide input voltage range.

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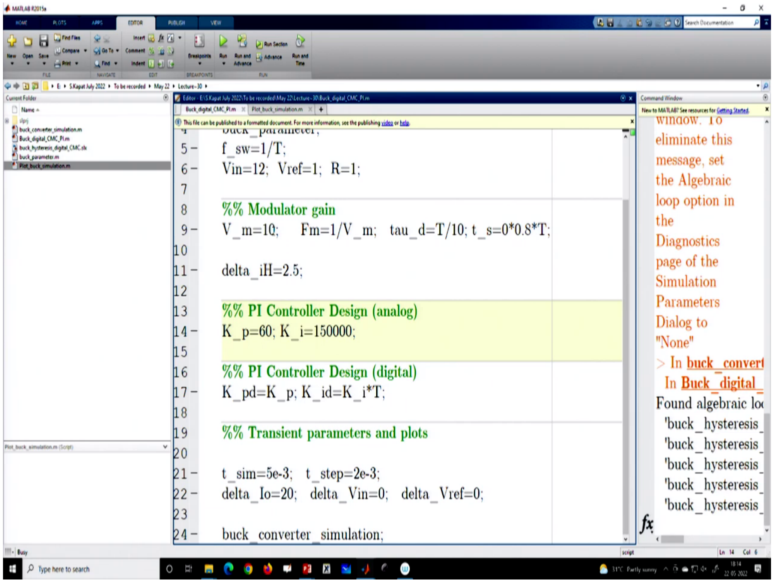

We are making a load step transient. So, we have set a very high proportional gain. So, let us say now let us run a simulation case study.

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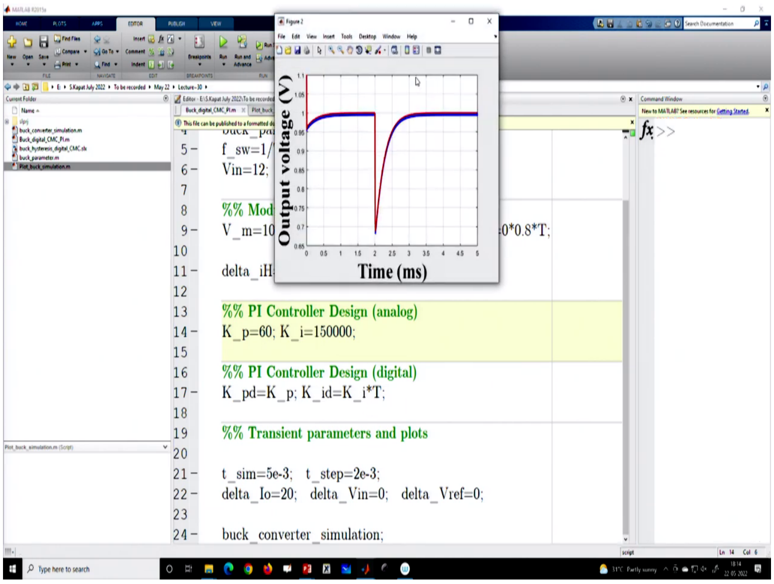

So, we are making a load step transient of 20 ampere.

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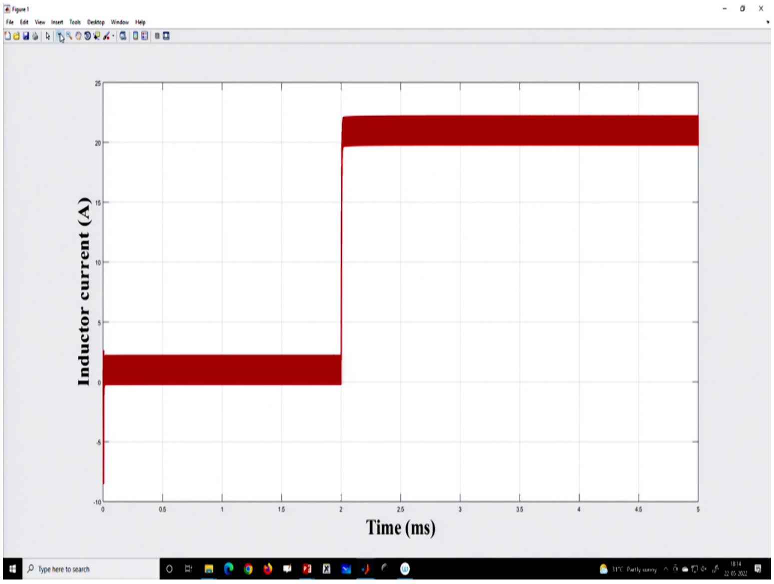

And this is a so what we have said is that the hysteresis current band is 2.5 ampere. So, you should expect that the actual current ripple should also be 2.5 ampere.

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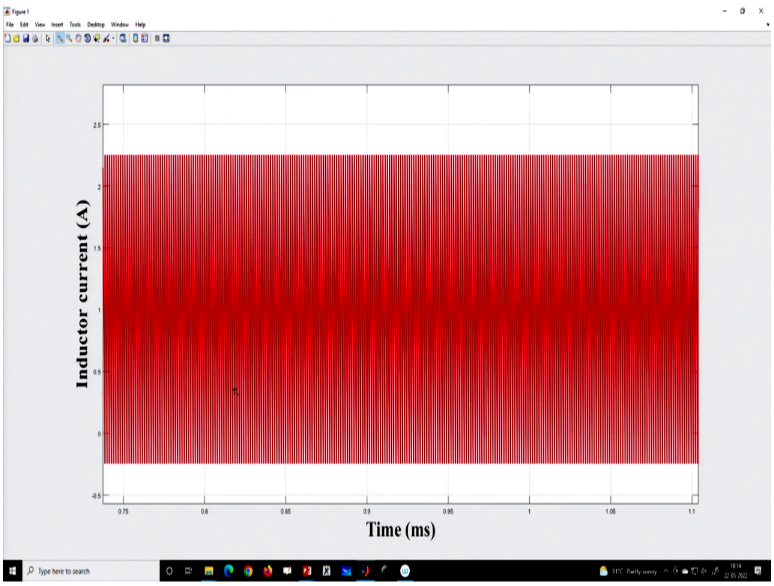

So, let us go and check if we go and check this band first.

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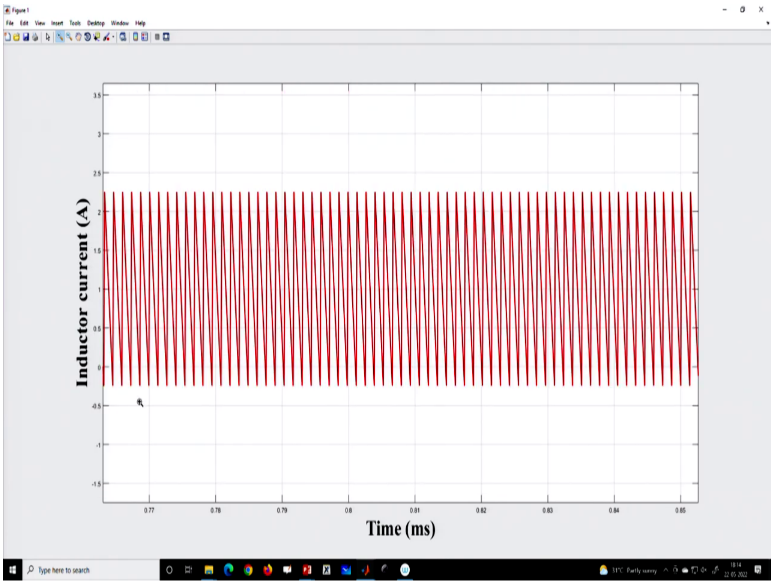

So, you can see it is varying between just above minus 0.5 and below 2.5; so that means, if you shift up from 0 it is exactly 2.5 ampere.

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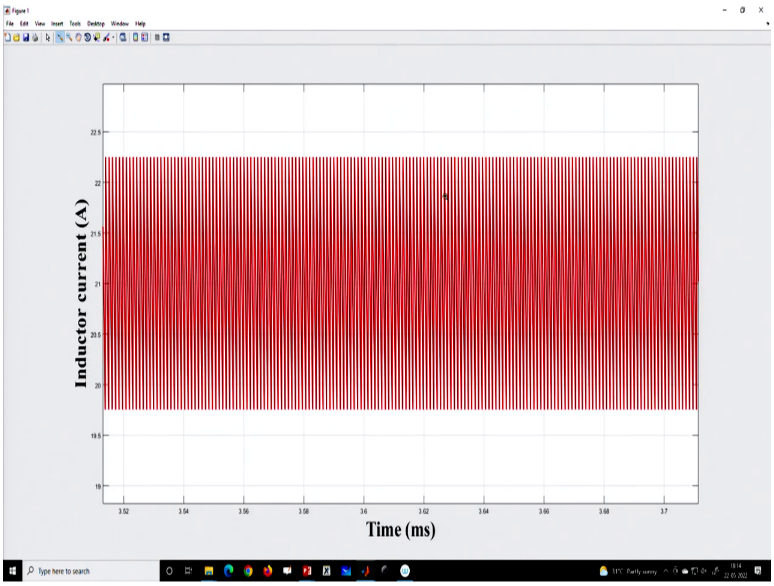

And if you go to the higher side.

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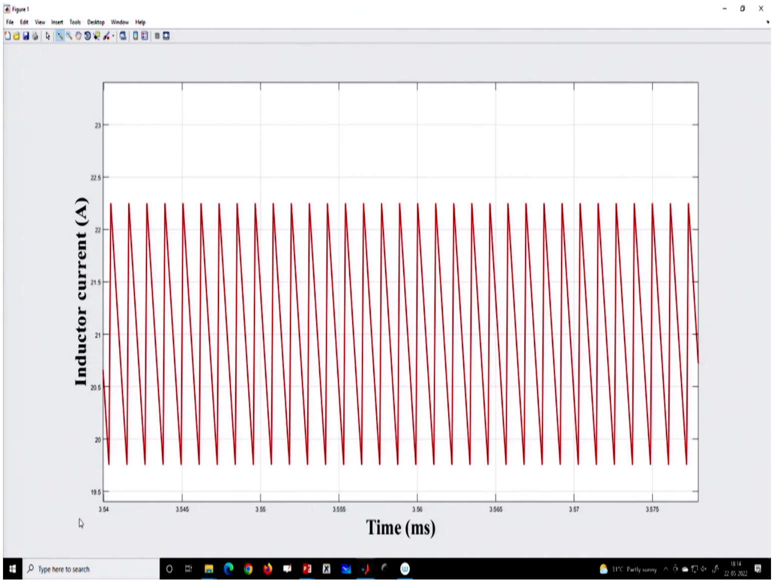

Here also it is just above 19.5 below 20.5; that means, if you take from 20 to 22.5 it is 2.5 only. So, it is also maintaining a 2.5 ampere ripple.

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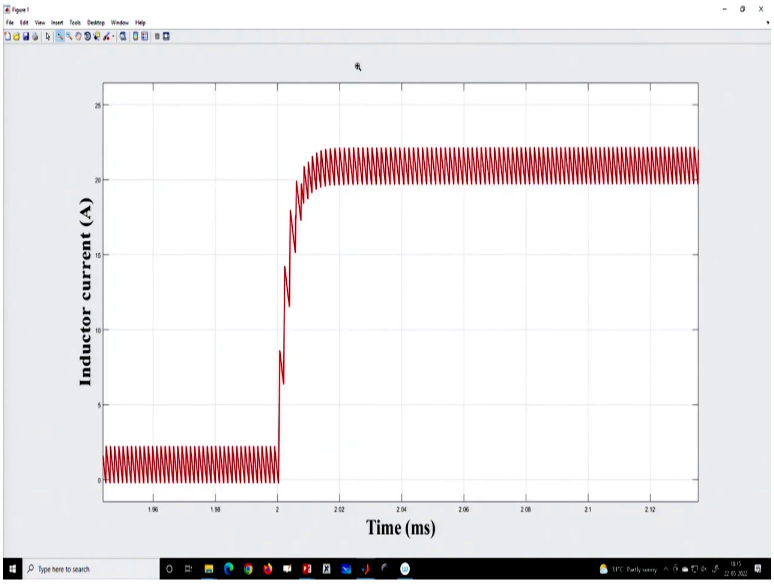

And we can improve the transient response very fast.

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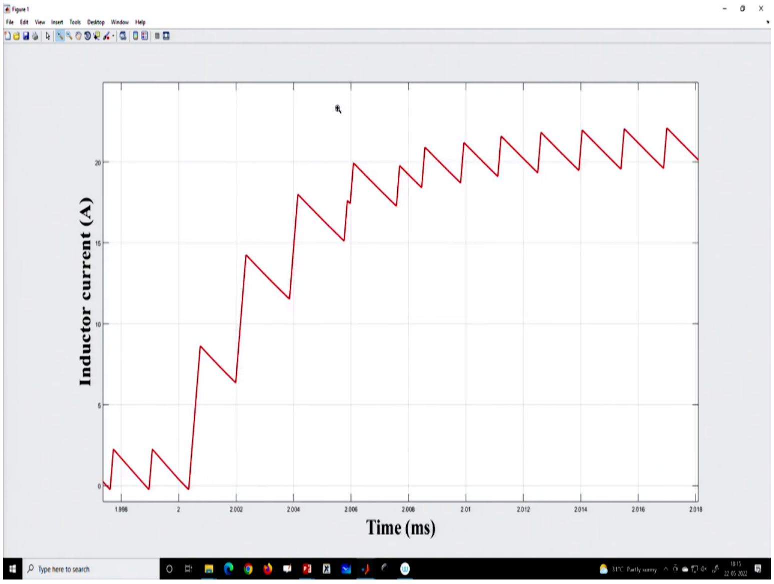

But here I am just showing that case study and you can see a first thing and I am showing the sampling process.

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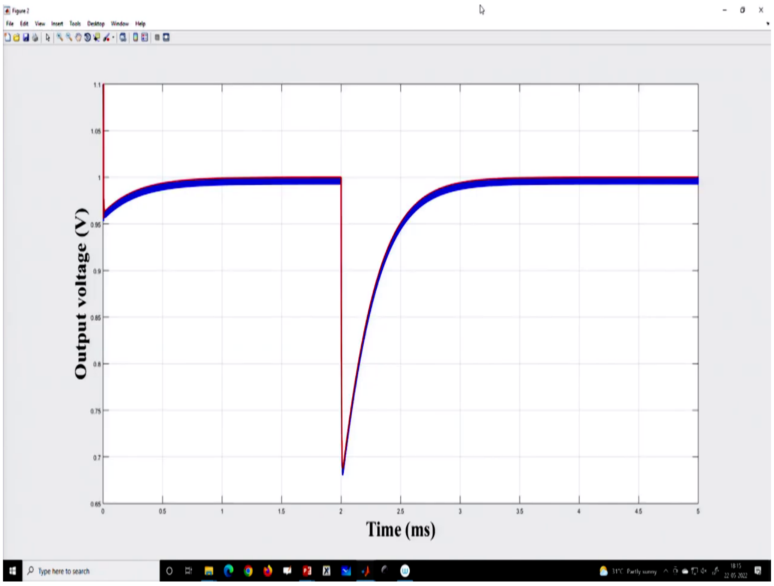

So, if you go here we are not considering any delay.

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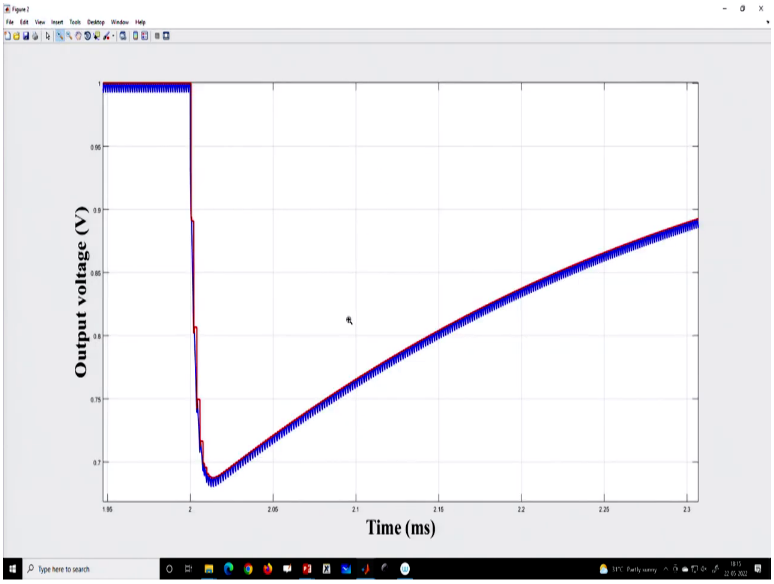

But it is an even base sampling.

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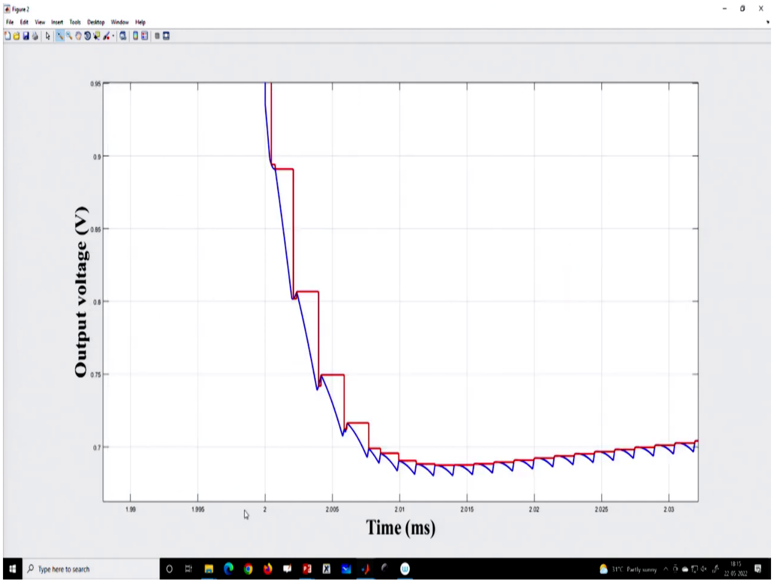

So, let us say when there is a transient.

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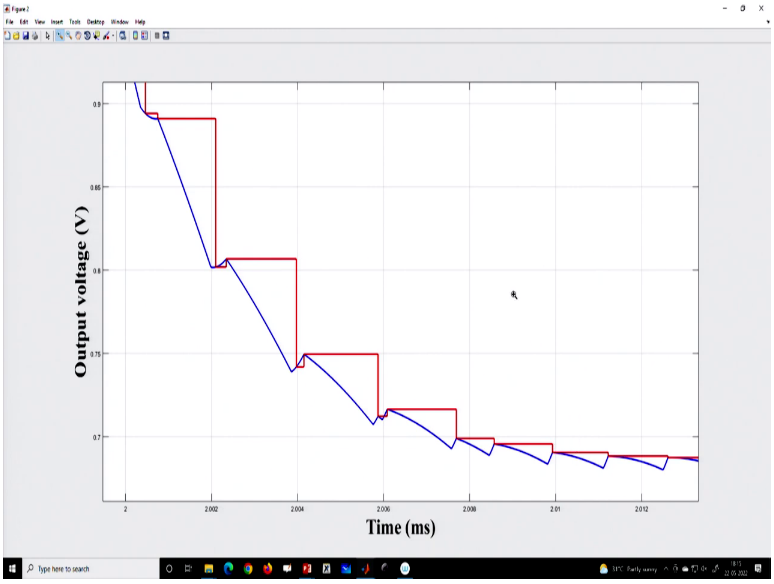

You can see depending on how it is hitting the band. So, you can see the sampling point is getting changed; that means, you know the voltage is a sample here when it changes here it is the same. So, it is getting updated here.

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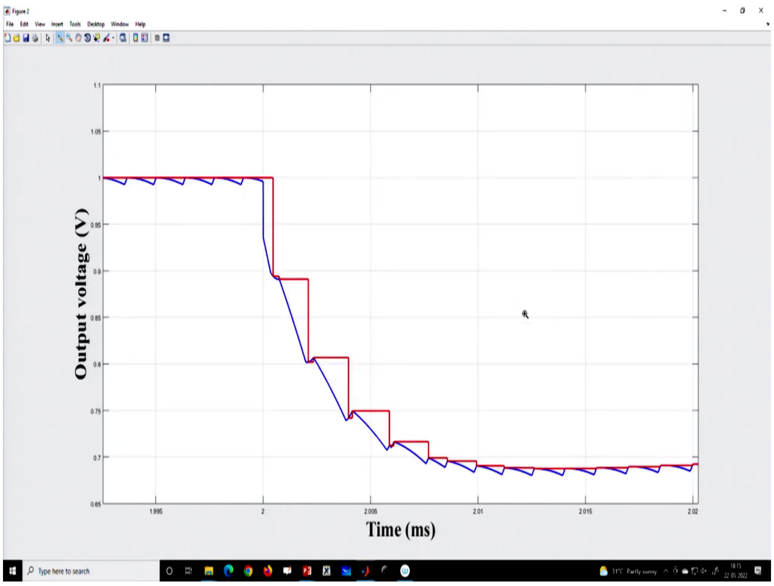

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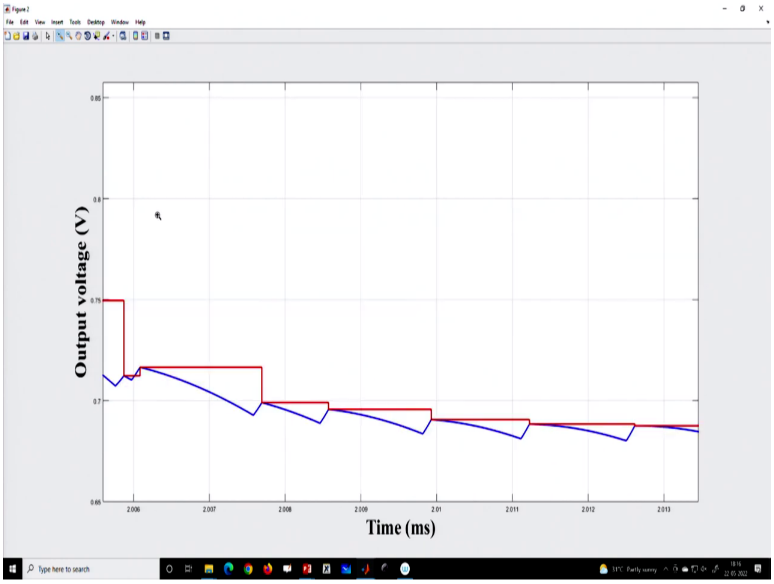

So that means, you are getting it like a very well time solver a very well time sampling because this is the duration of sampling is varying based on the time period of the hysteresis controller. That means, instantaneously the time period is varying when there is a transient.

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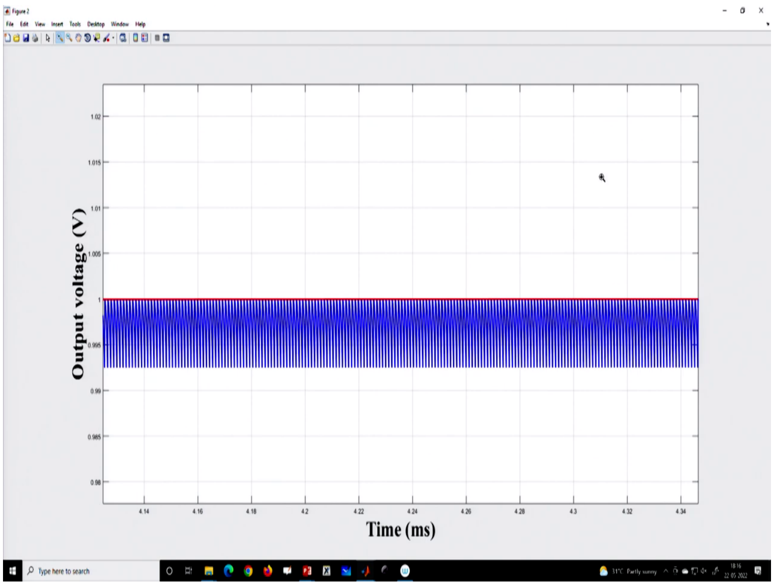

But when it reaches a steady state.

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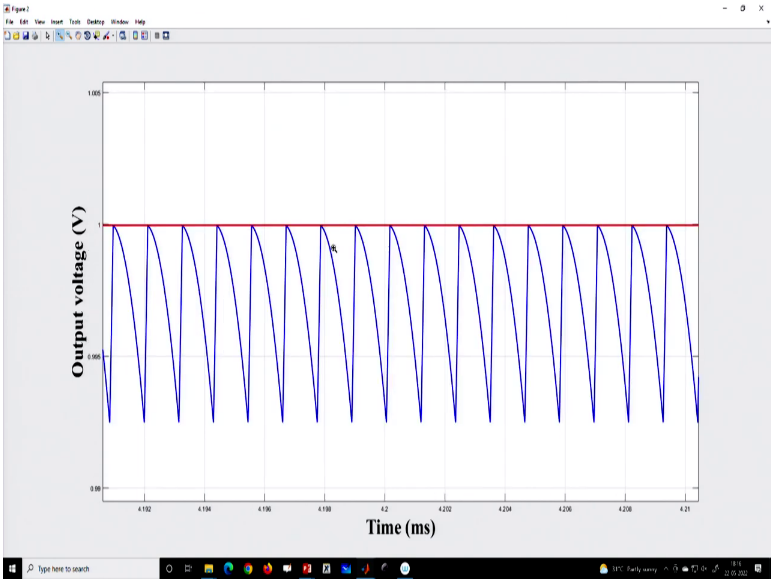

Then it is more or less fixed.

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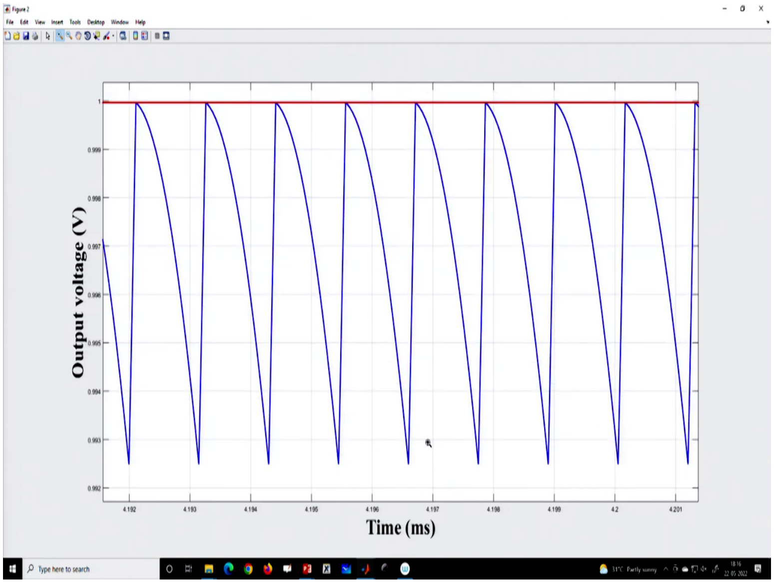

And then your output voltage sample also get fixed.

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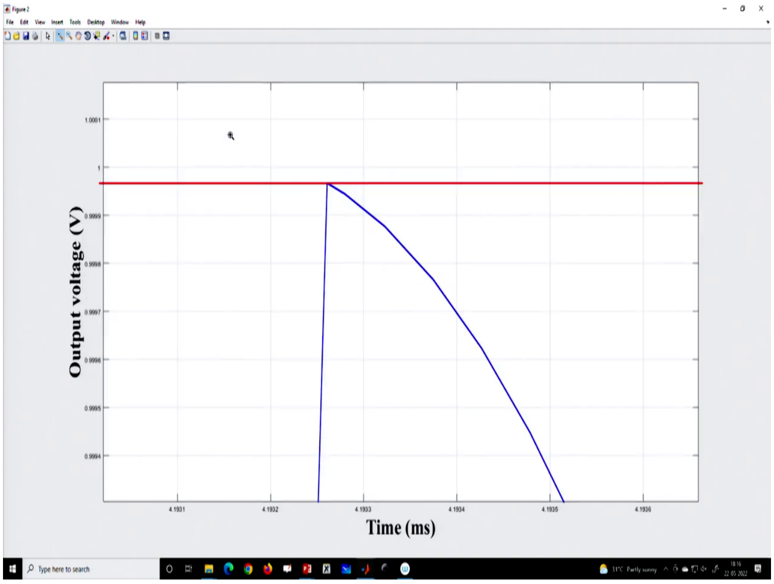

But since we are sampling at the peak value of the output voltage.

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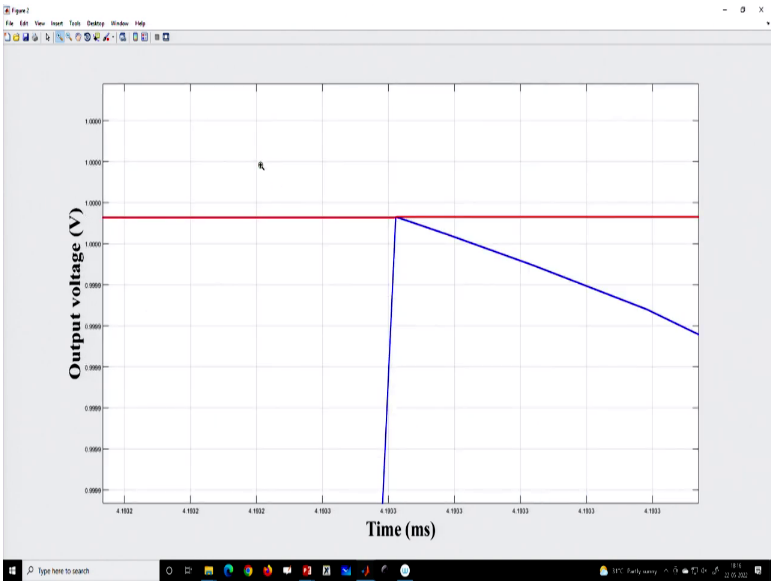

You see the peak value is regulated to 1 volt.

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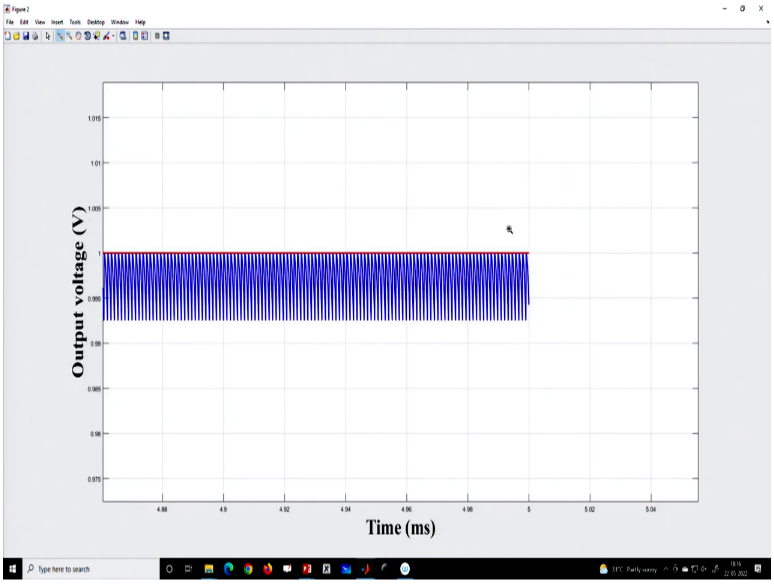

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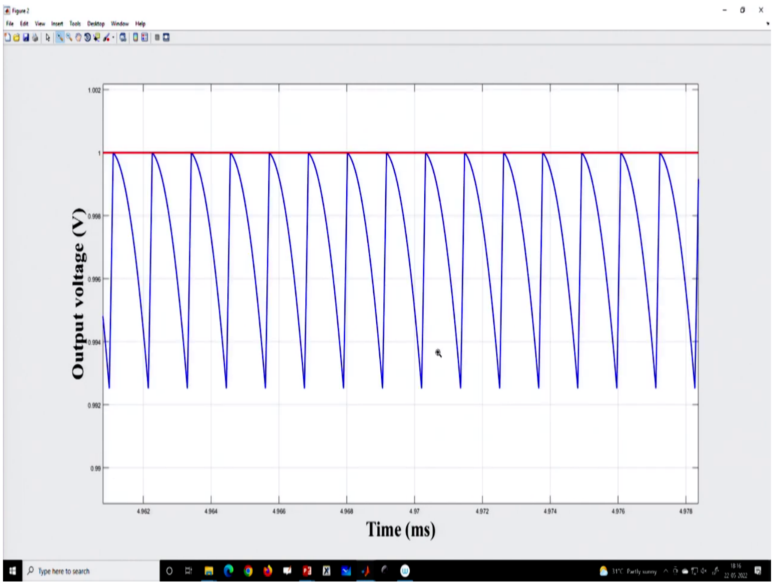

But your average voltage is lower. So, you may suffer from the regulation issue. So, you have to address this issue of what should be the right sampling point otherwise you may lose the regulation point. Similarly, if you use a valley current base valley voltage is based on a valley hysteresis current mode control, and if you take the sample at the valley point.

So, the voltage will be go will go up; that means, your valley point will be regulated at 1 volt. But the average voltage can be higher. So, here it is lower now if we go to let us say we want to change the input voltage.

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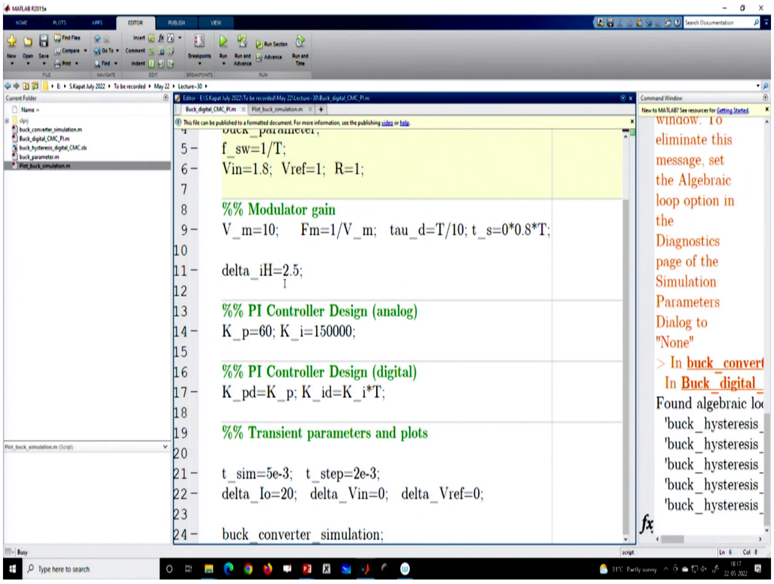

Let us say we are going for 1.8 volt for 1-volt output.

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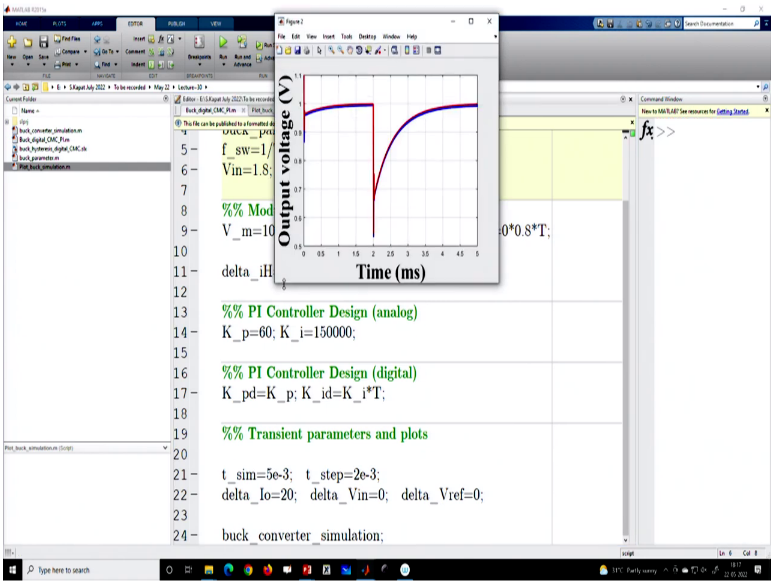

So, let us run the simulation c.

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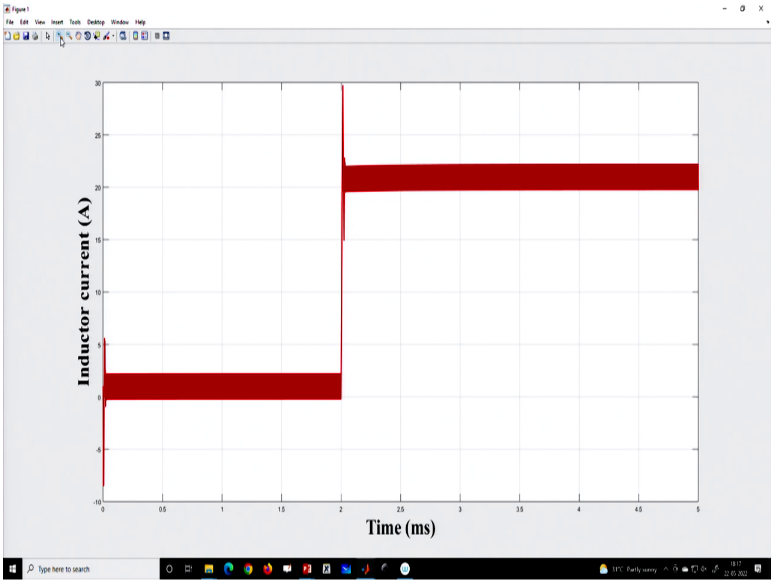

So, there is no current loop stability as such, but yeah of course there is a transient issue.

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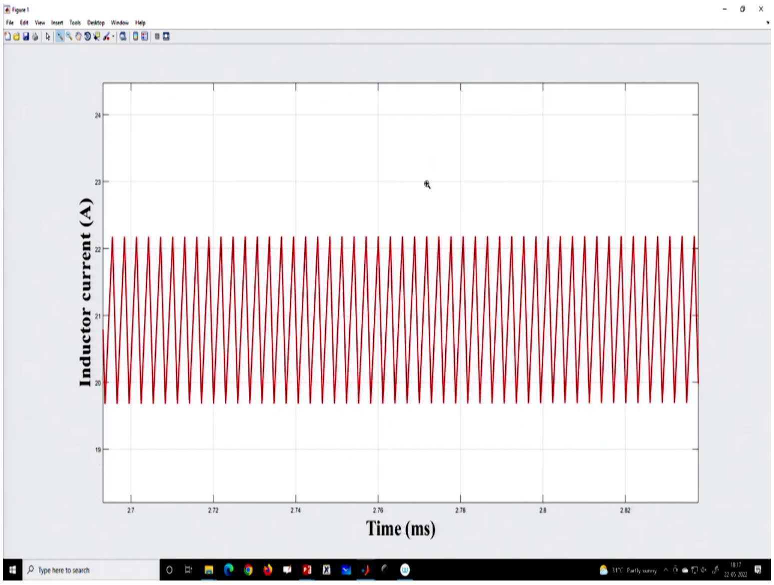

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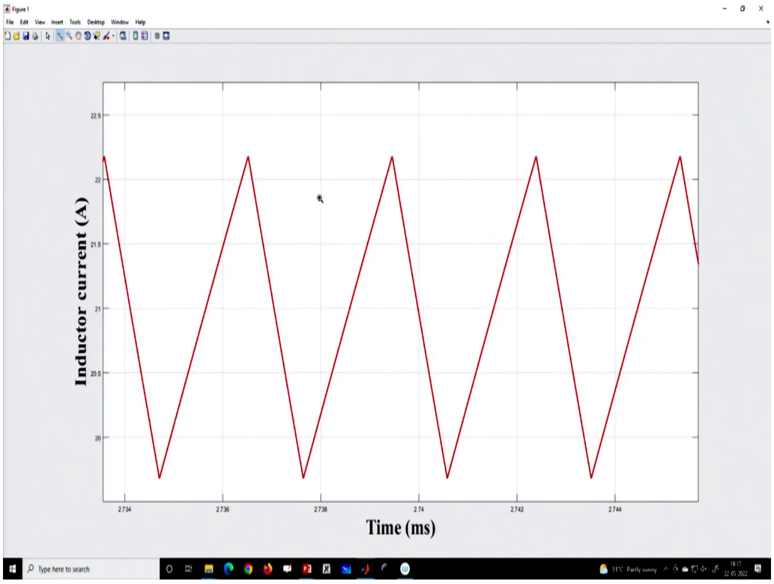

But you can see the output voltage ripple is still maintained.

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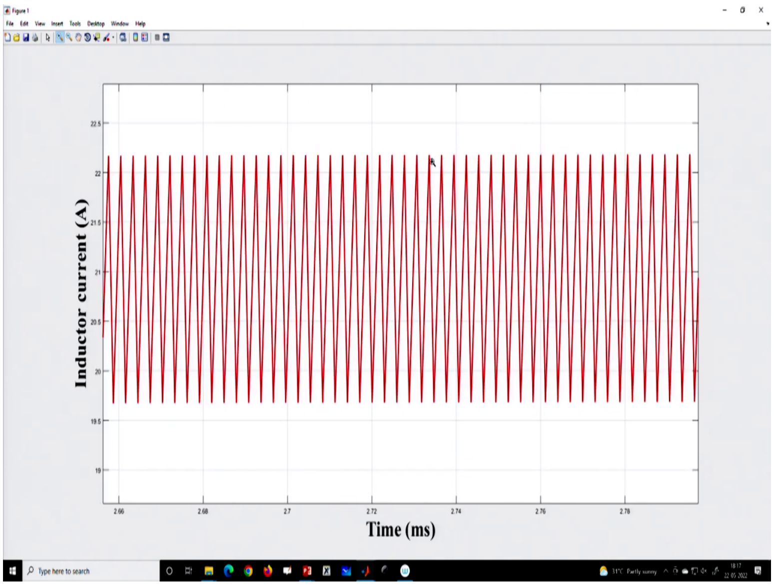

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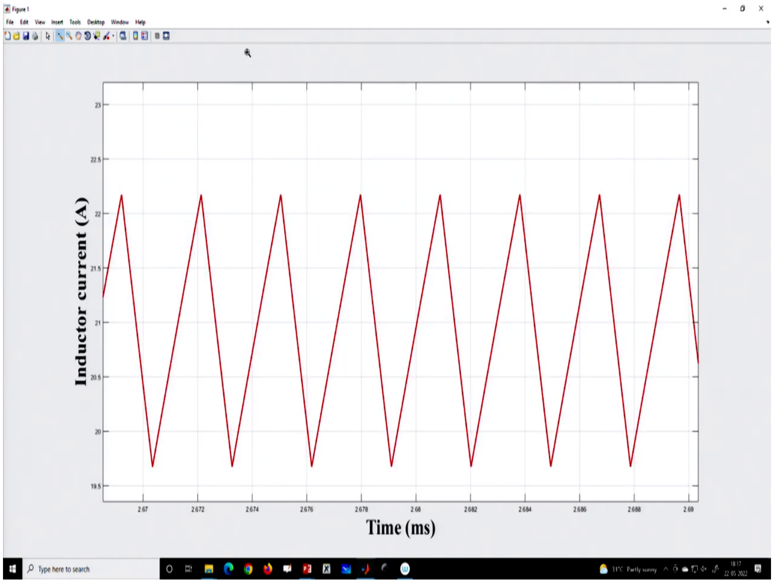

At almost 2.5 so you can see the same.

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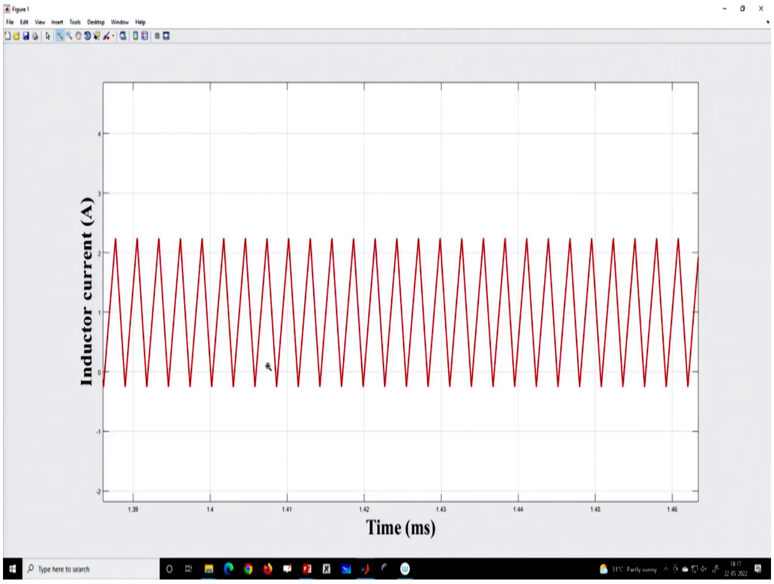

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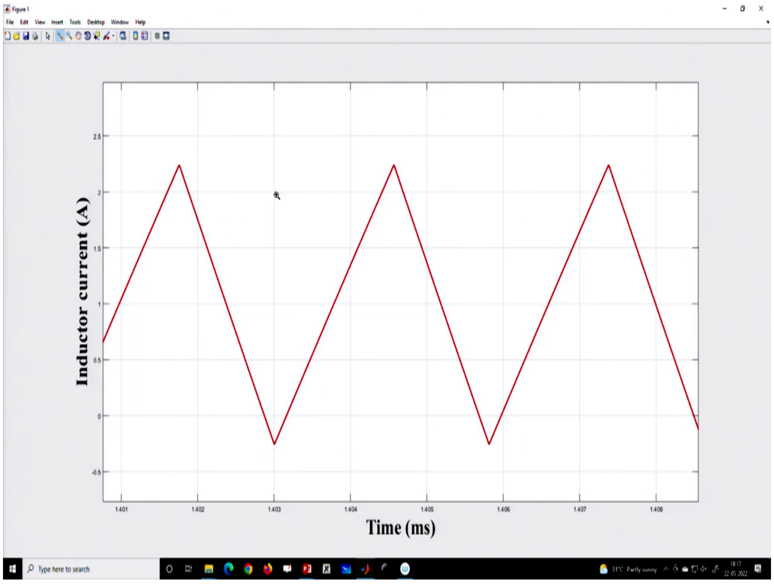

There is no change in the output the inductor current ripple is maintained.

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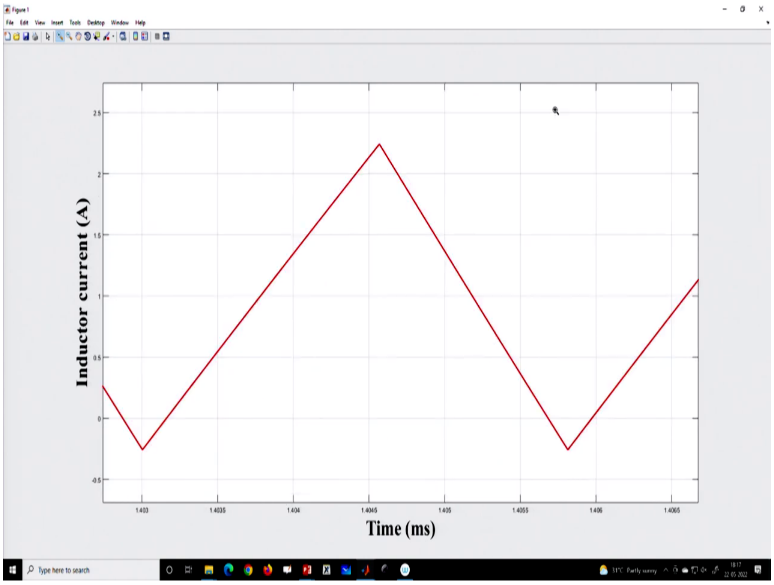

But the time period is drastically varying, so you can see it is more or less approaching three microsecond; where our desired time period was two microsecond. So, your time period has increased or the frequency has decreased because you are you have decreased the input voltage. But yet you have maintained the same current ripple, but if you take a regular DC converter fixed frequency. What happens? If we keep on decreasing.

The input voltage then will happen the current ripple should decrease and if you increase the output input voltage, the current ripple increases for the fixed frequency control. But in this case, since you are keeping the current ripple the same. So, naturally, the time period is increasing ok; so which means it is a variable frequency operation.

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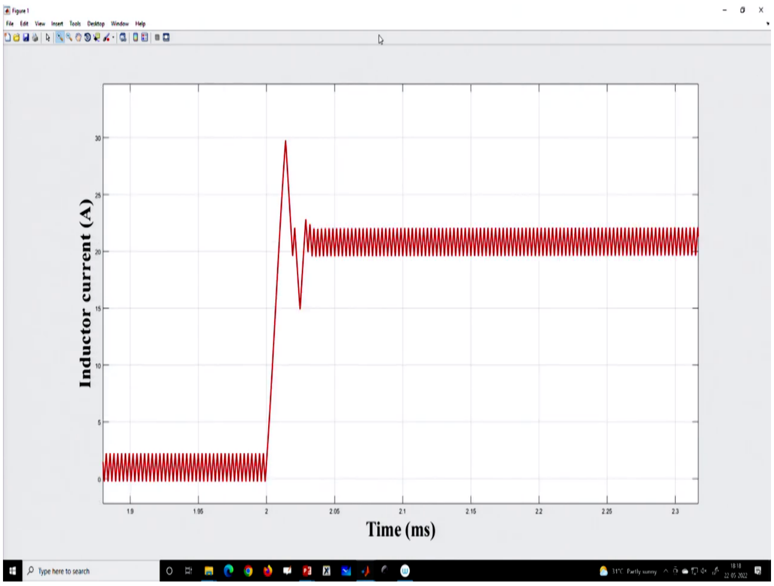

And you can adjust the hysteresis band.

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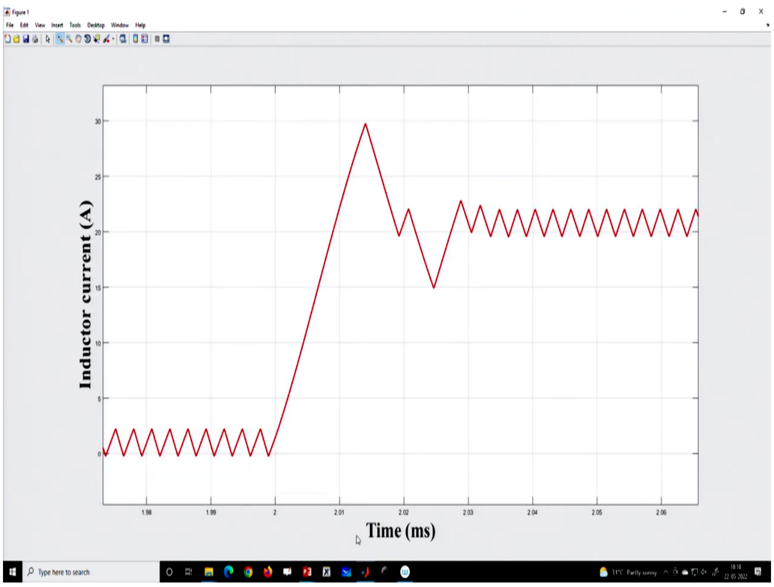

If you want to regulate the output voltage.

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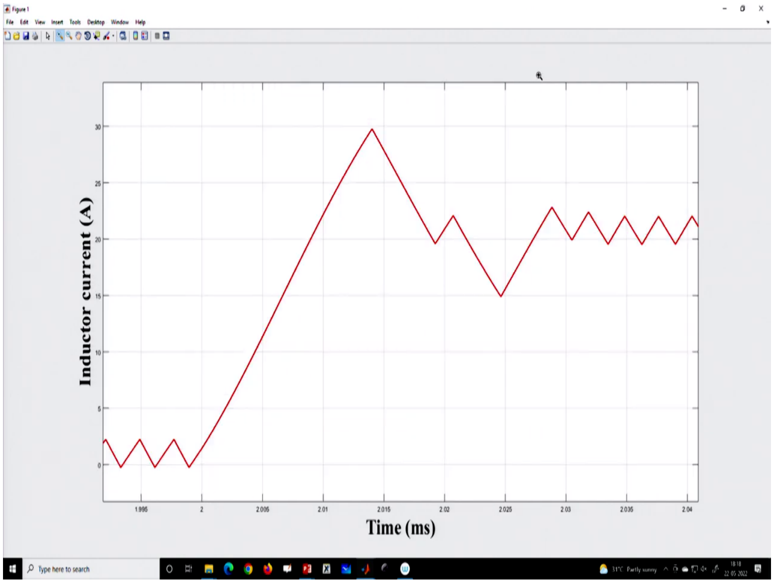

But you can see the response is pretty fast ok and you can get ultra power.

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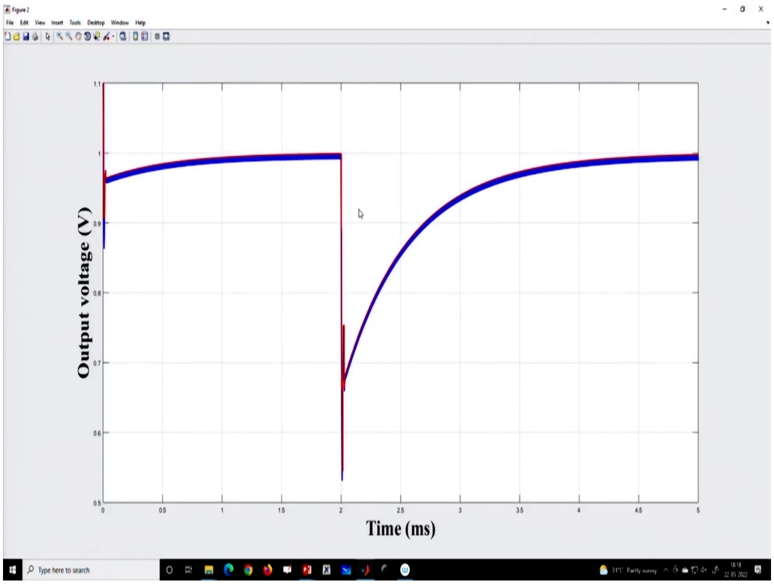

Because hysteresis control is considered to be one of the fastest control.

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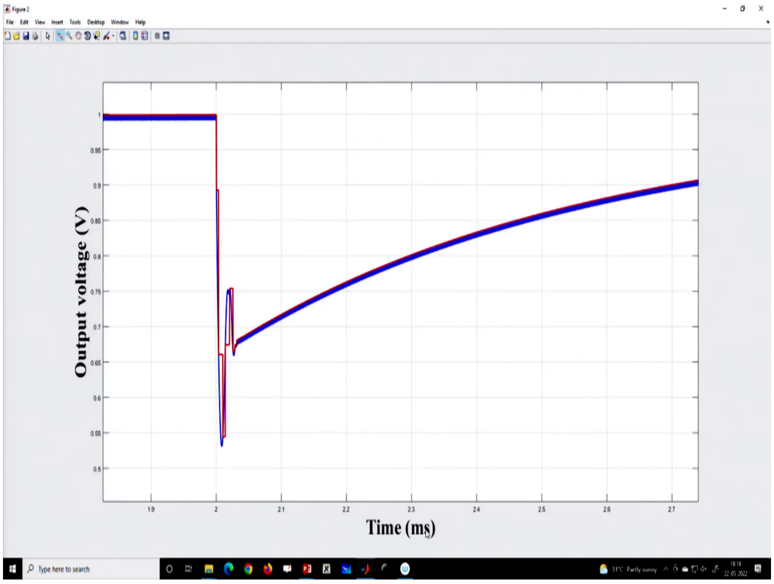

But how do you make a digital control realization? So, this is one example using mixed-signal hysteresis control. We can also take one case study of reference voltage transient.

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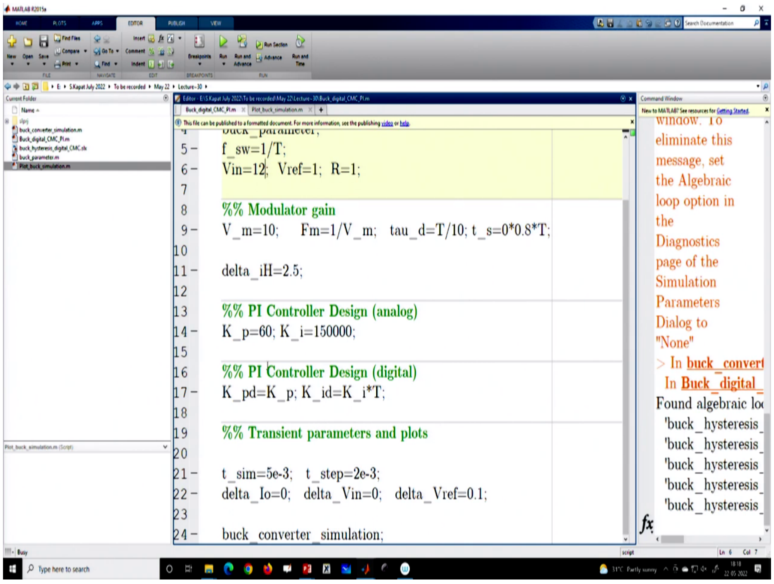

So that means, we can take 0.1 and we can now use let us say 12-volt input ok. So, this is another case study.

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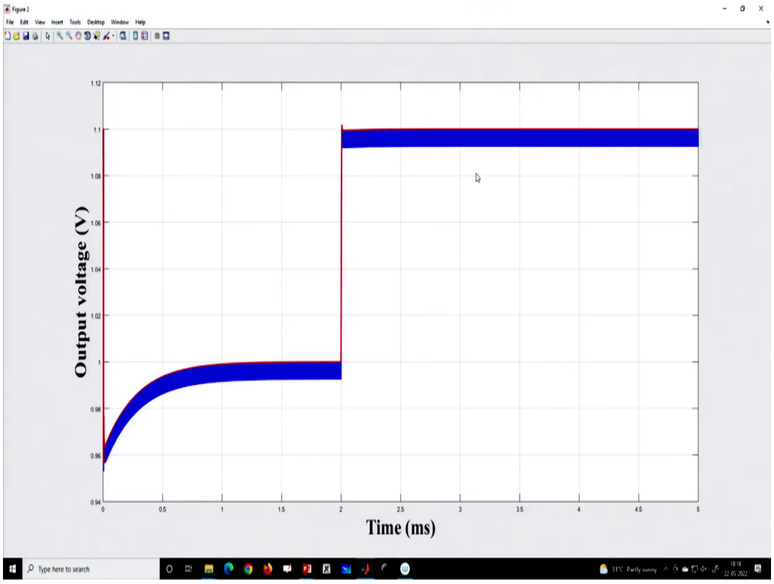

So, here you can see the response is very very fast.

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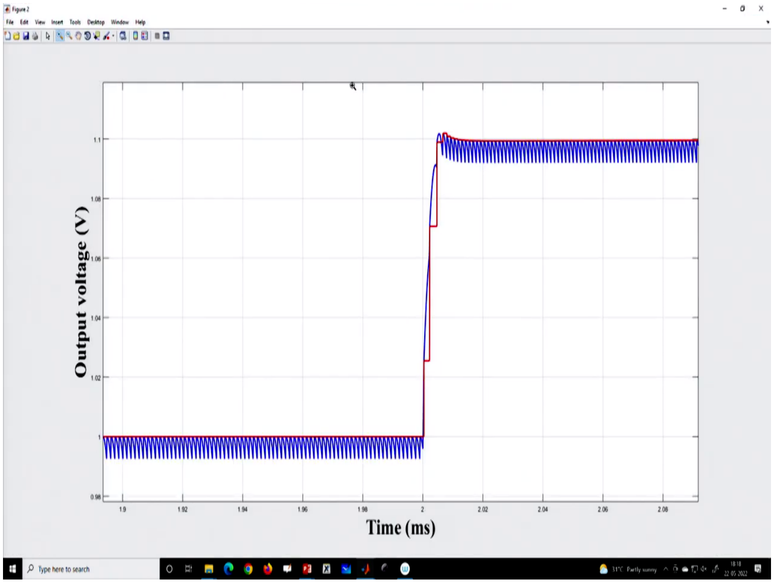

That is a very fast transient response.

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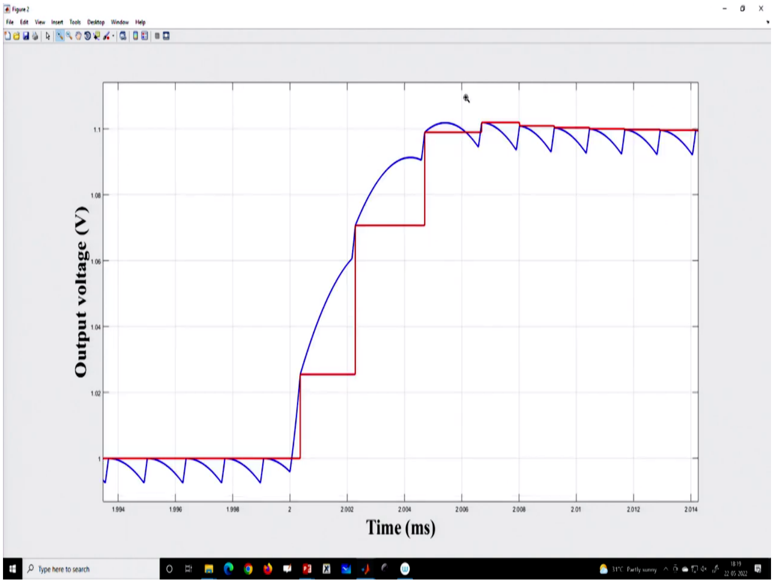

Again you can see the sampling rate is varying.

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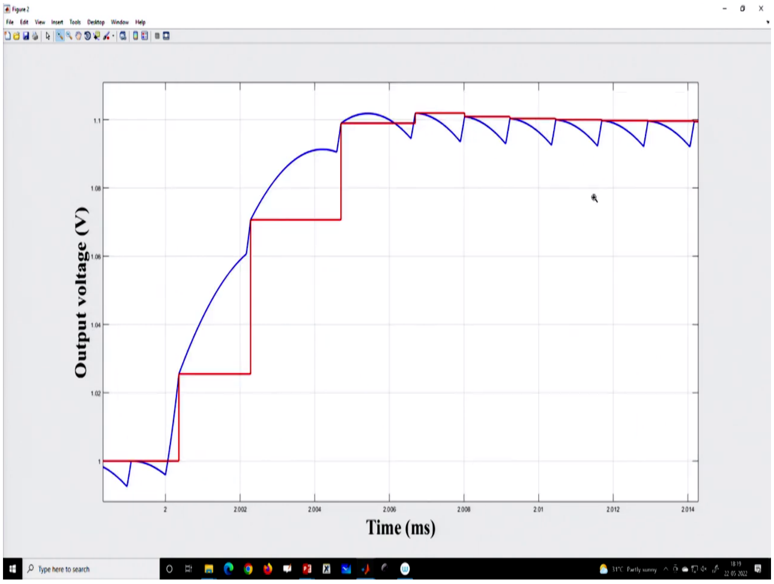

You know if you consider that in between inter-sample. So, this may be problematic because if this is a large transient and if there is less number of events, then your sampling actual rate is reduced.

So, and you know we have discussed in the research paper, that if we because this may even sometimes maybe if you further increase the voltage may collapse because you may not get the actual output voltage information. So, the best way if the sampling duration exceeds a certain threshold value, then we can do a forceful sampling. So that means, we need to combine event-based and uniform sampling during the large signal transient. So, that the output will not collapse as well as you can maintain a fast transient recovery. But when it comes close to a steady state we can go for it.

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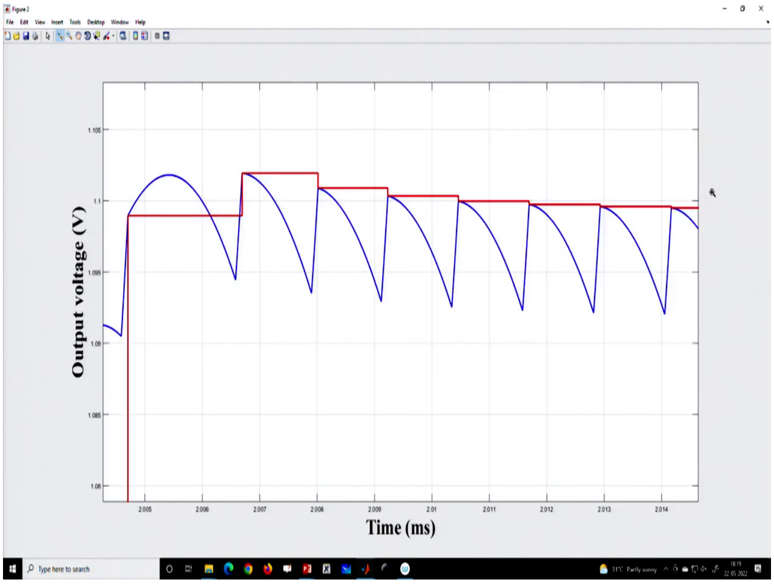

You know event-based sampling, but in this course, we are not discussing this.

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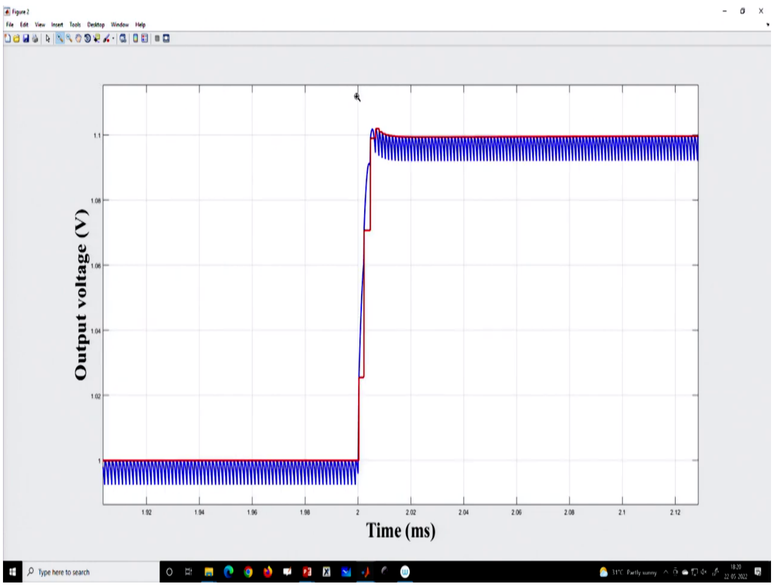

Because this is a very advanced topic, the here only thing you can remember is that we are using throughout event-based sampling.

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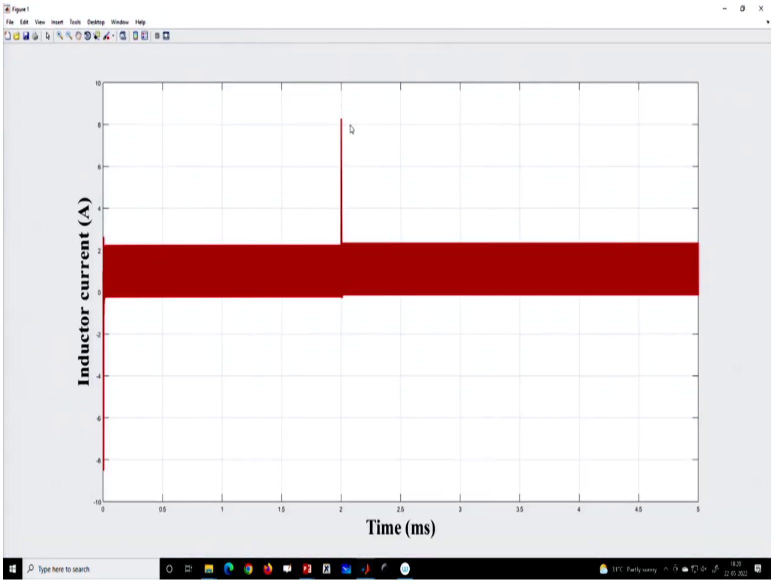

And we can get a very fast transient response which is also evident from the inductor current waveform ok.

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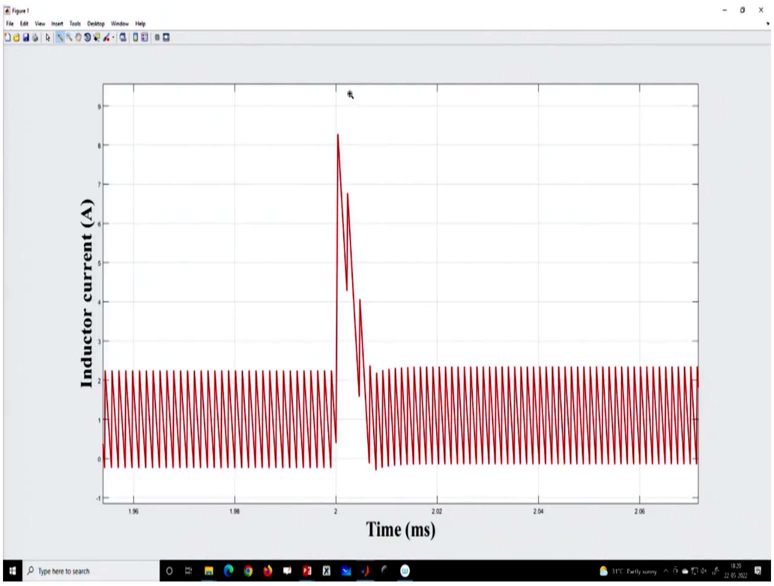

So that means, we have discussed the various case study under the peak current-based mixed signal hysteresis control.

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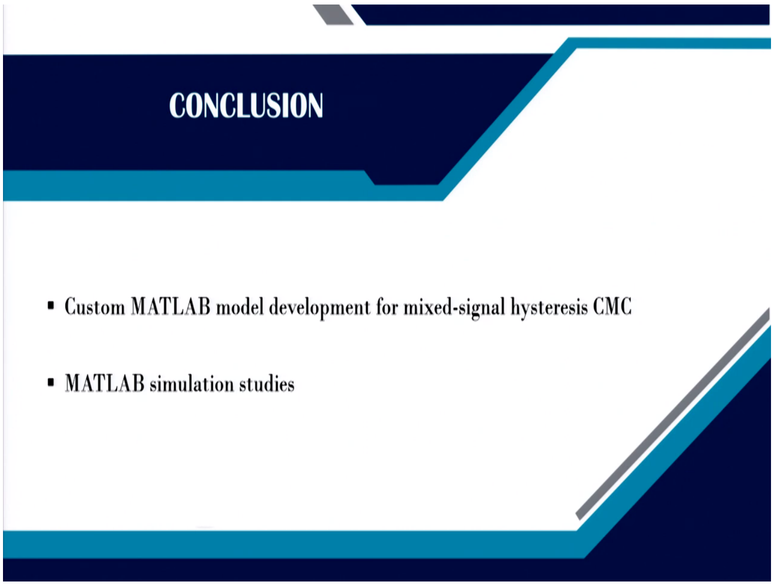

So, in summary, we have discussed custom MATLAB model development for mixed-signal hysteresis current mode control and we have also considered a few simulation case studies. And I think so this we will next week we will talk about MATLAB like a model modeling of a digitally controlled converter. So, this way will more or less know we are going to finish the MATLAB model development for various digital control architectures. That is it for today.

Thank you very much.