Control and Tuning Methods in Switched Mode Power Converters
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Module - 12
Performance Comparison and Simulation
Lecture - 54
Nonlinear Control vs. Large-Signal Tuning: Comparative Study Using MATLAB

Welcome this is lecture number 54. In this lecture, we are going to consider Nonlinear Control and Nonlinear Tuning Large-Signal Tuning Method, Comparative Study and MATLAB Simulation.

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So, here, we will first summarize the nonlinear control and tuning method that we are going to consider then, MATLAB implementation of nonlinear control method and tuning methods then, simulation of nonlinear control and nonlinear tuning method. We have considered both buck and boost converters and a comparative study.

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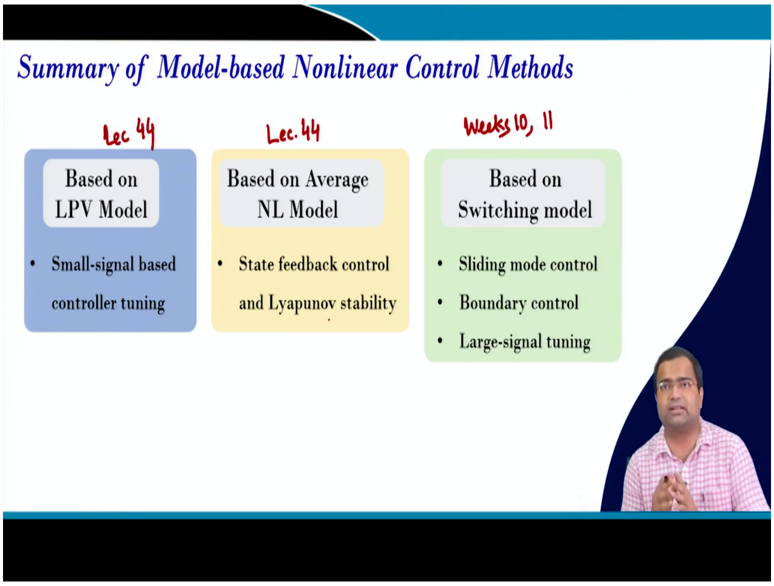

So, first, we want to summarize what are the control method that we have considered in this lecture. We are going to consider, one is the linear parameter model, linear parameter varying model-based control and average nonlinear model-based control and switching model-based control.

So, in the linear parameter varying model-based control, those things we have already discussed. I think this we have discussed in lecture number 44. So, you get detail in lecture 44 here. You will also get detail in lecture number 44 here, and here we have considered all like a week you know, week I think week 10 as well as week 11. So, all these discussions we have made, ok.

Then, state feedback control and Lyapunov based stability, and then sliding mode control, boundary control and large-signal tuning. These are the control methods which we have considered in this lecture.

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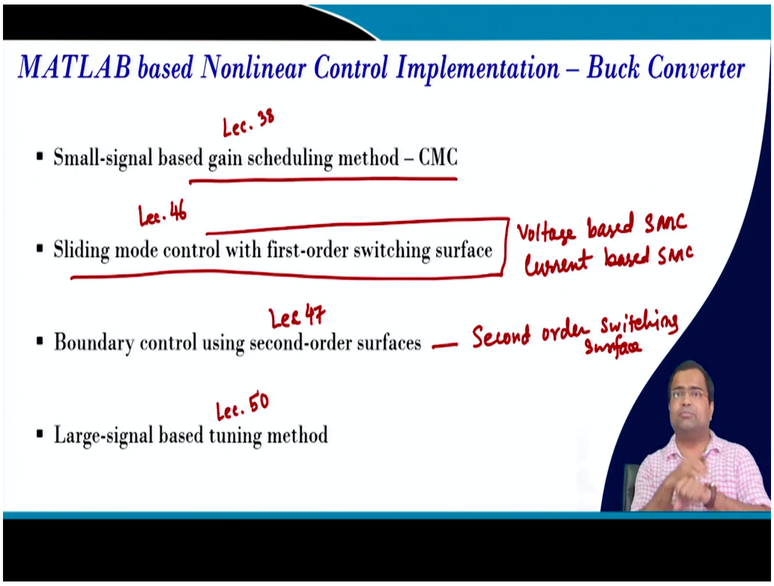

So, first we will consider the MATLAB in a buck converter, what is the MATLAB case study we are going to consider. One is the current mode control, where we have designed based on traditional tuning, like pole zero cancellation, stable pole zero cancellation.

Then, we are going to consider sliding mode control with first order switching surface. And here we will consider both voltage based sliding mode control that means, we will consider both voltage based sliding mode control where we will have output voltage and the derivative of the output voltage. And we will also consider current based sliding mode control. Here we are going to consider inductor current and output voltage. In both cases, output voltage is common because we need to regulate the output voltage.

Then, we have also considered a second order switching surface; you know the boundary control using second order switching surface, second order switching surface. And this thing we have discussed in week lecture 47. This we have discussed in lecture 47. And this thing we have discussed in lecture 46, ok. And this thing we have discussed in lecture number, I think in current mode control 38. So, all this we have already discussed, ok.

And then the large-signal based tuning method, and which also we have discussed in lecture number I think 50. So, we are just summarizing and with MATLAB case study.

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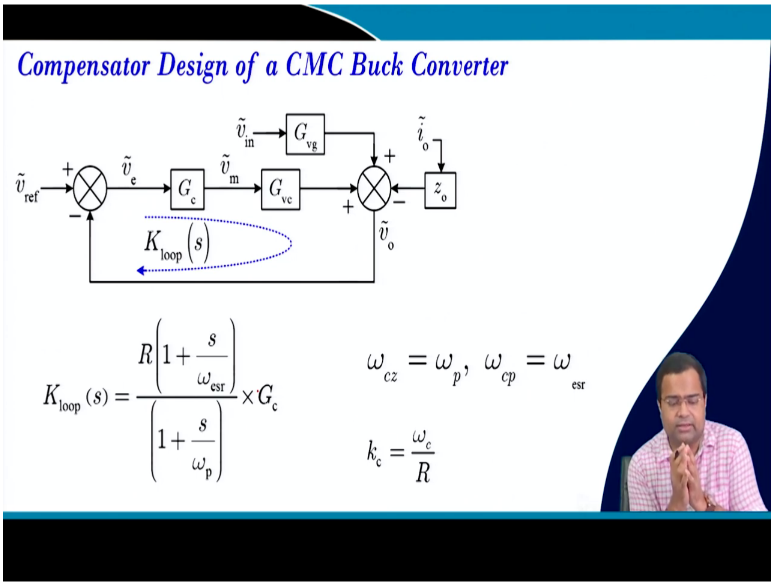

First, if we take current mode control. This is standard as I told, if you go to lecture number 40, sorry not 40, lecture number 30, I think it was up to current mode control 38, ok. So, how to place poles and all these things we have discussed. So, I am not going to discuss here.

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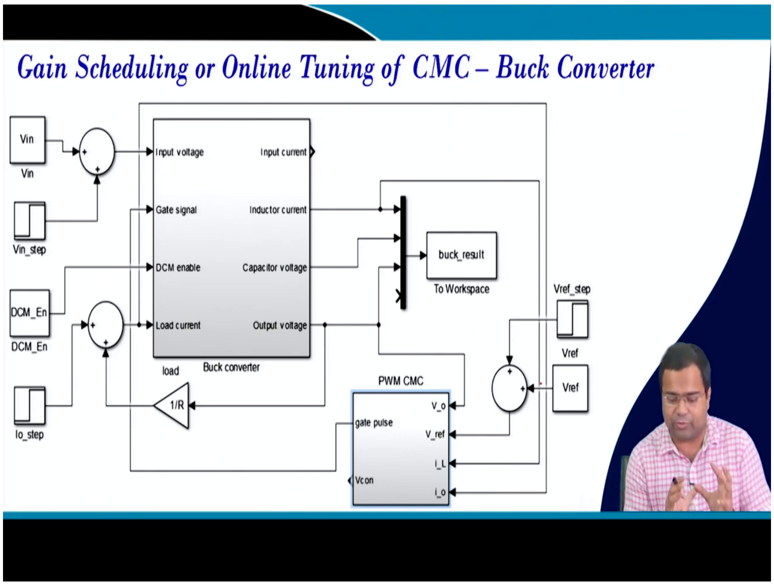

Then, we know how to implement current mode control. This we have discussed multiple time, and this is my current mode control structure.

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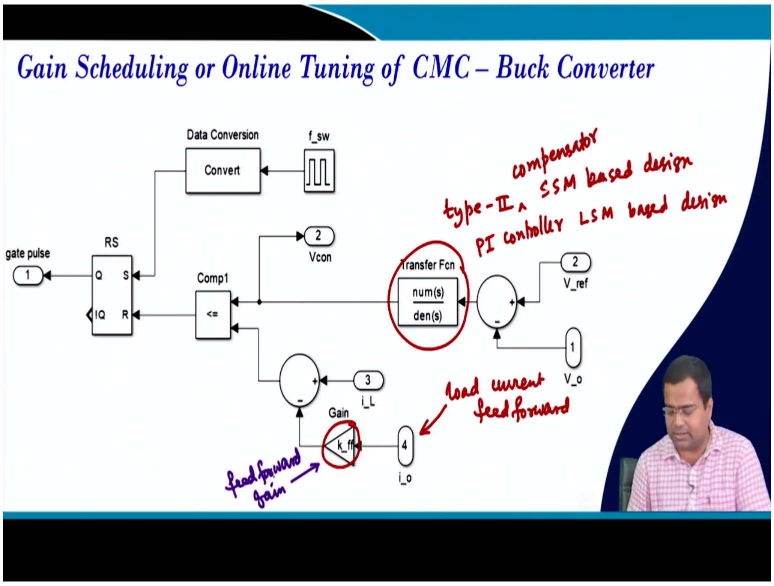

And if you go inside here, you have a transfer function where we consider type-II compensator, type-II compensator. But in case of our large-signal tuning, we are considering. So, this is for small-signal based design.

And in our case, we will consider a PI control. So, this is type 3 compensator. So, in our PI controller, we will use large-signal based, large-signal model-based design, ok. And this is our load current feed forward. So, this is our load current feed forward. Particularly, this term is load current feed forward, not this term, where this indicates our feedforward gain, right?

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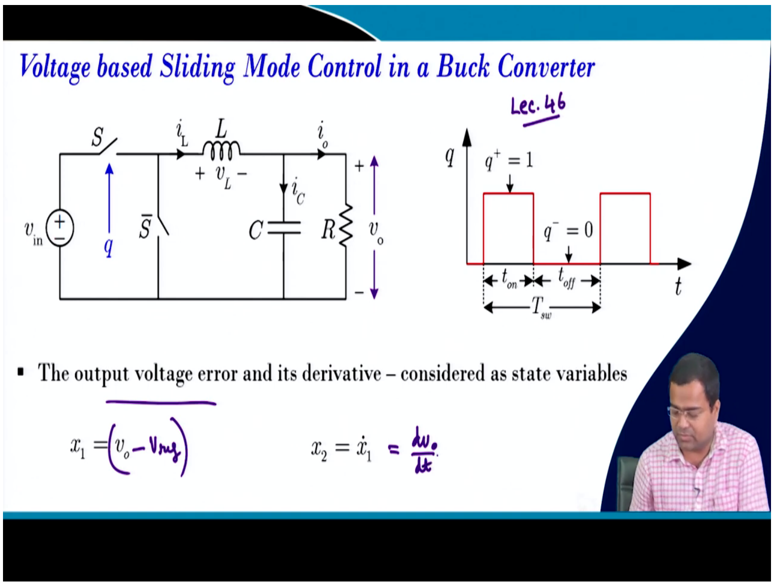

Then, we are going to talk about voltage base based sliding mode control in a buck converter which we have discussed in detail in lecture number, so this we have discussed in detail in lecture number 46, ok. So, here we are considering error voltage and its derivative at the state. So, you can take the error voltage at the state is v 0, v ref, at the state and the other is x 2 dot equal to x 1, which is simply dv 0, dt, ok.

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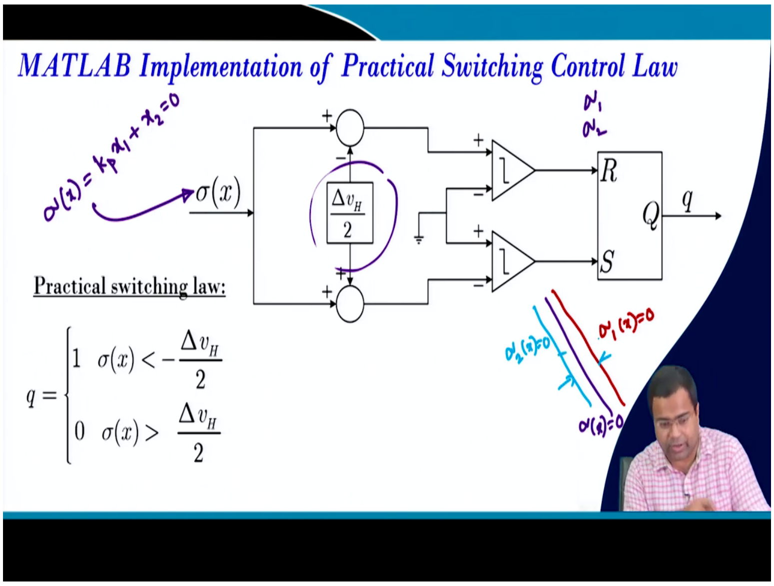

And in this switching surface sigma x, what we have considered is that K 1 or K p into x 1 plus x 2 is equal to 0. This is our switching surface, ok and this is our hysteresis band that we have discussed because we will want to get sigma 1 x and sigma 2 x, because if we have this line this is our sigma x equal to 0. Then, what we want to find? We also want to get a band sigma 1 x equal to 0 and we also want to get sigma 2 x equal to 0, ok. So, this is the band and this band we are defining in terms of voltage because it is along the y axis like voltage x.

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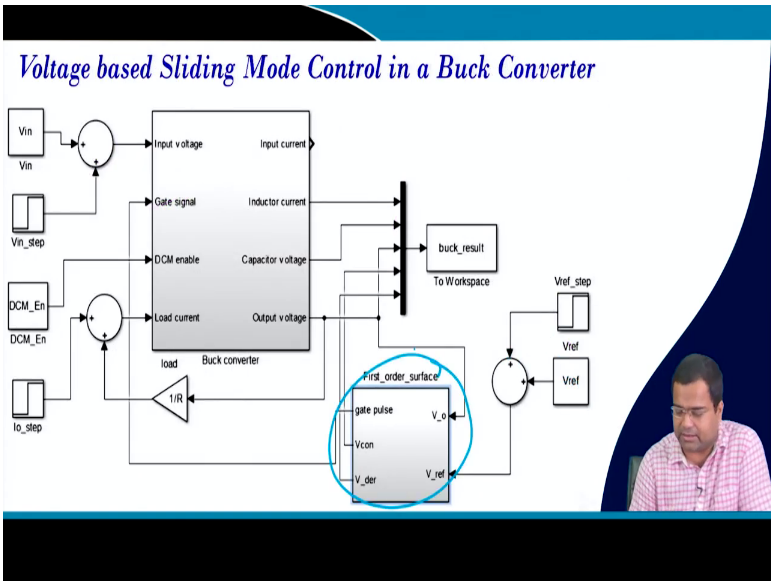

So, we can implement this voltage based control and that we have discussed in lecture number 46, where this is our you know band limited derivative action, ok. So, this is the voltage derivative.

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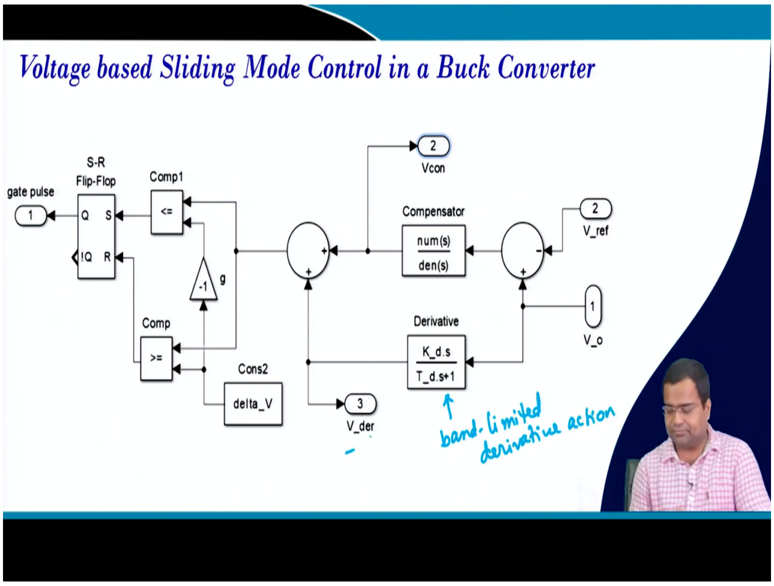

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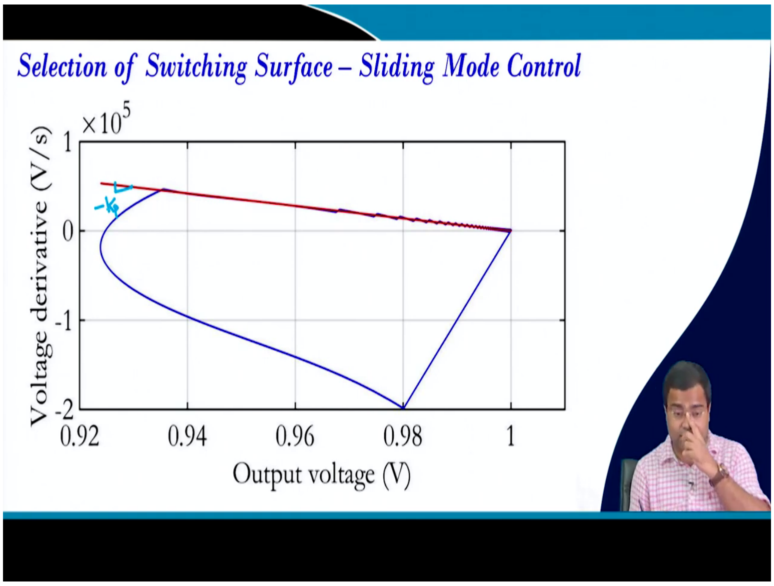

And this we are going to consider MATLAB case study. It will look something like this depending upon the slope of this surface minus K p, ok. Because if you increase the slope K p, then the slope magnitude will increase, and you will you can speed up the response, but we will see what are the different possibilities.

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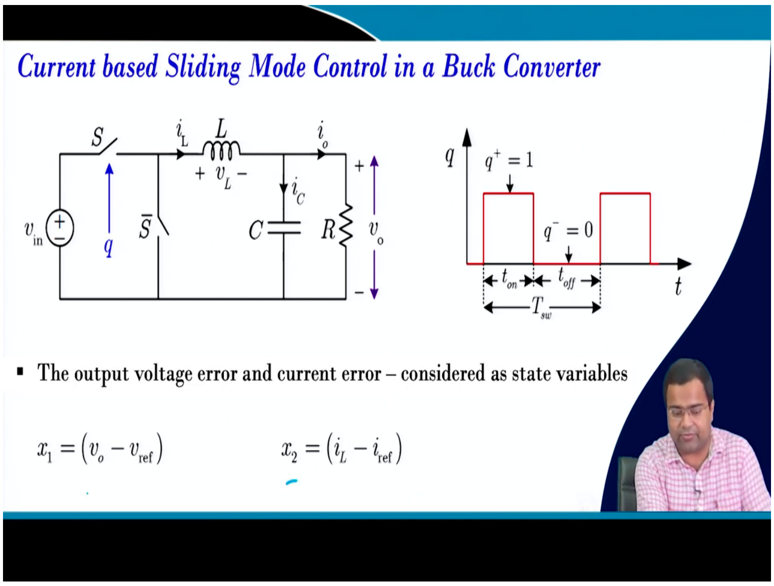

Then, current based control. In current based control, we can you know use inductor current is one of the state variable output voltage, another state variable, you can take error current and error voltage at the state.

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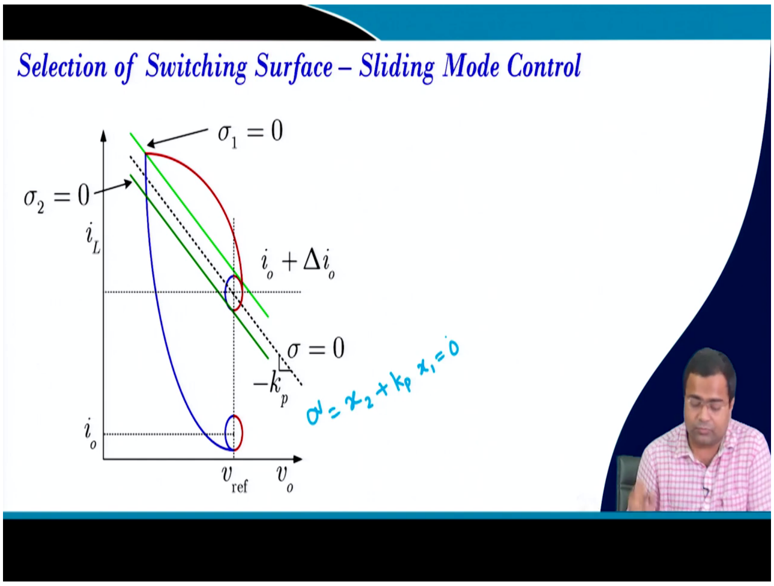

And we know how to form this. So, this sigma in this case will be x 1 the error current plus K p into. So, we will check what is x 1 is the error voltage, ok. So, I am sorry, it should be sigma will be you know x 2 plus K p into x 1, x 1, right K p into x 1. So, no bracket here and this should be equal to 0, ok.

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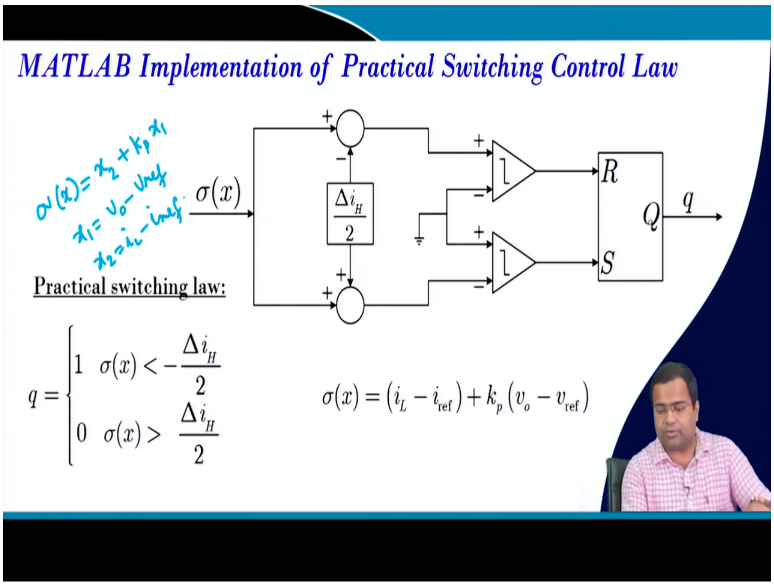

And we know how to implement. So, this we have discussed, sigma x that means, our it is a current based one. So, x 2 plus K p into x 1, where x 1 is our v 0 minus v ref and x 2 is our inductor current minus reference current, ok. So, this is what I have discussed.

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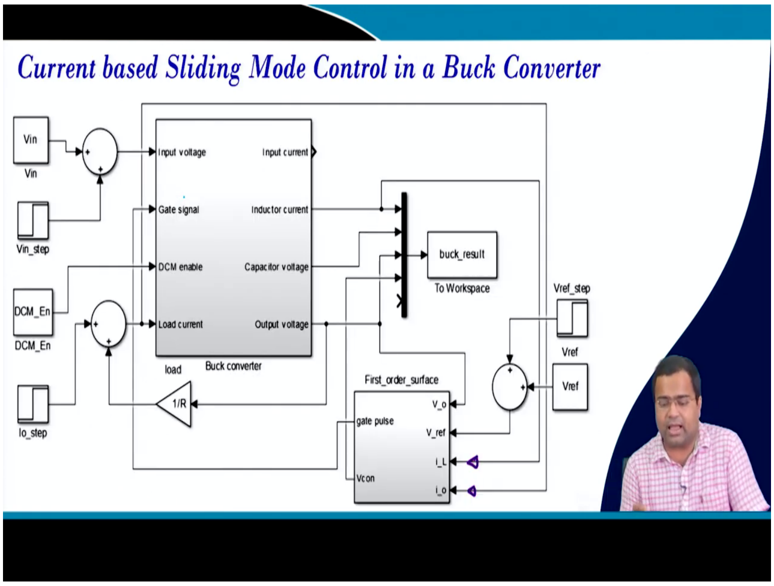

And if you want to implement, then you need to consider this inductor current feedback, load feedback, and this is what is our i L minus i 0, in this case we have taken this is my x 2 and this is our x 1, ok.

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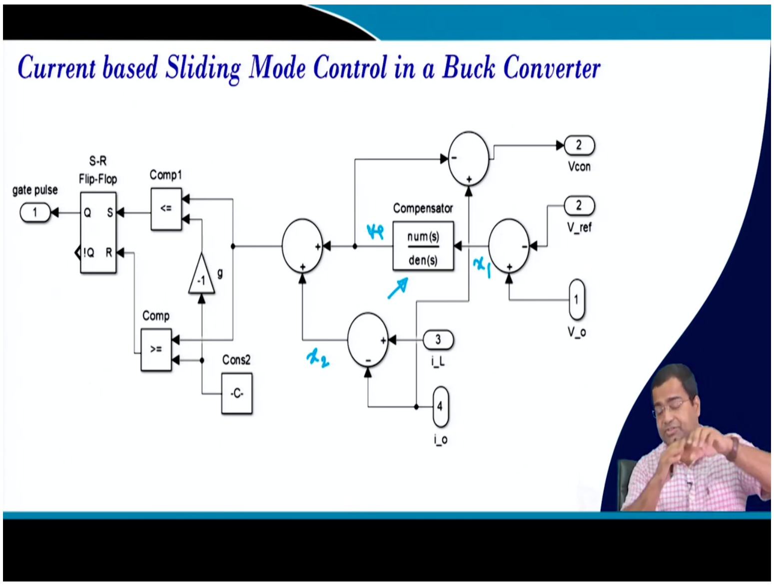

So, you can simply use the proportional gain k p here. But we can also include integral action, then your switching surface will no longer remain a straight line because integral action will try to increase. So, you cannot again define into a first order like a sliding dynamics, so it will again become a second order. Because integral action, it time sorry, time integral actually can create that surface structure will not be straight line, ok.

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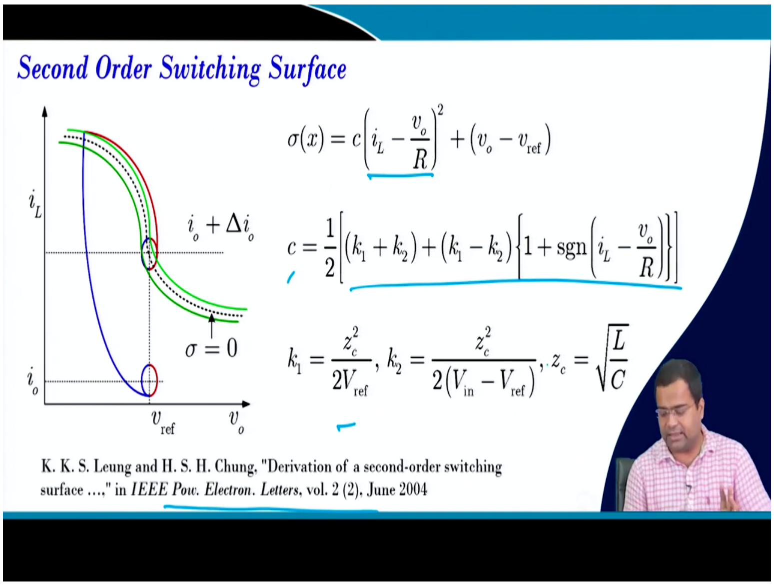

And we have also considered second order switching surface, where this surface you know how to discuss design the second order switching surface. It is discussed in this paper that we have taken the current error square into some constant into voltage. And this constant can be constructed using a sigmoid signum function where k 1, k 2 are a function of characteristic impedance, and their reference voltage and input voltage like this.

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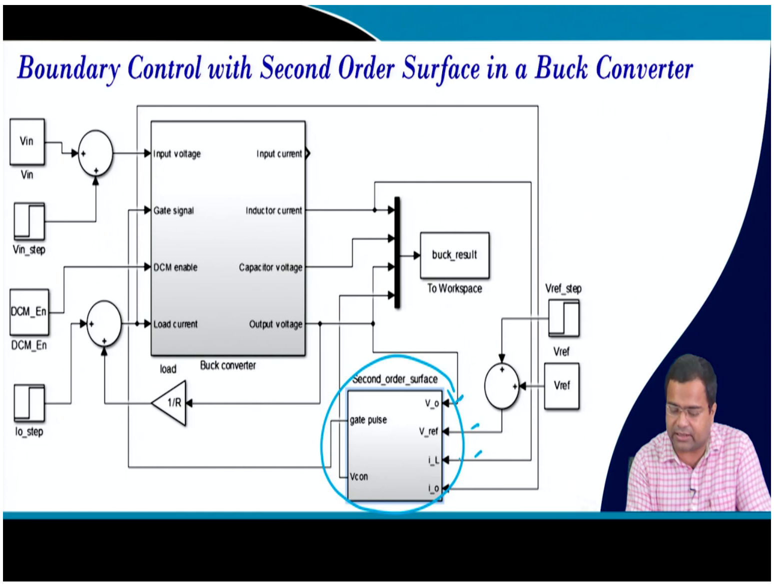

So, let us, and the boundary control if you want to do MATLAB implementation. So, this is our controller, everything else remains same. We are sensing voltage, reference voltage, inductor current, load current.

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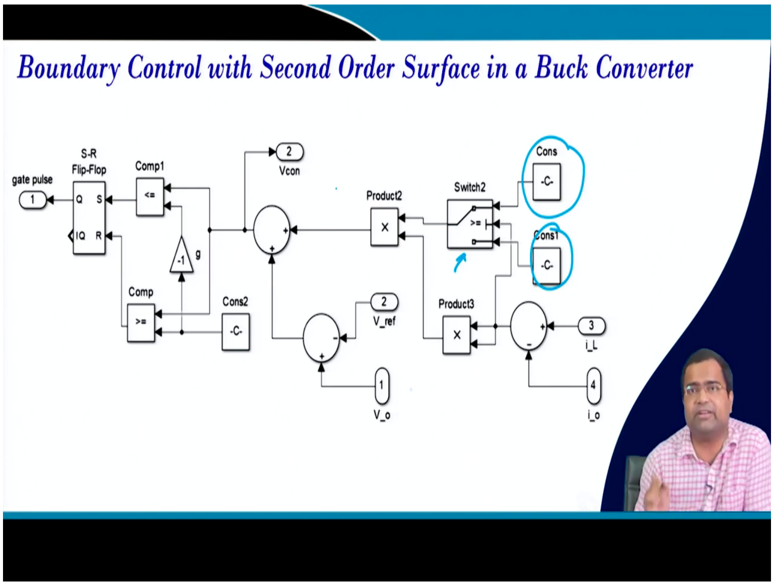

And then, here these two constants that we have discussed k 1, k 2, and then, along with this you know this function of reference voltage input voltage, characteristic impedance and this product. And then the switching logic will be there because there is a signum function, right? And then we have an error voltage here. This is our error voltage, voltage minus this and then this is the implementation.

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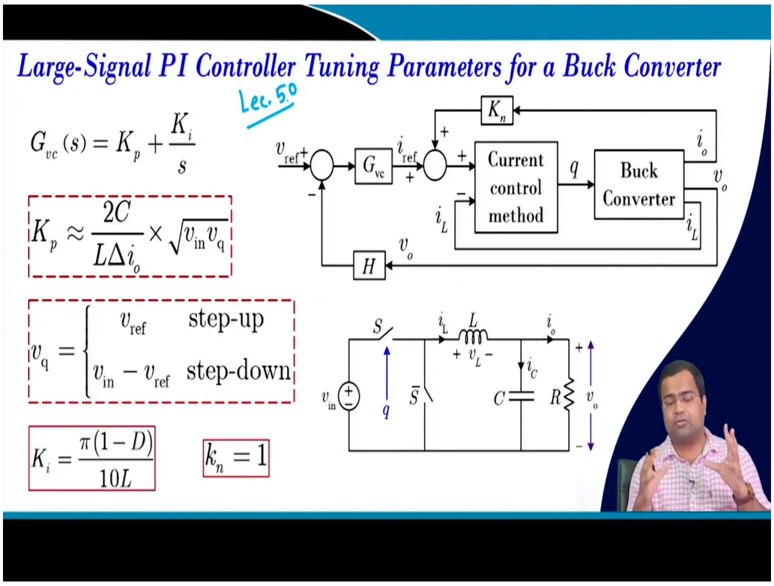

So, and we are also considered large-signal PI controller tuning. This we have already discussed multiple times you know if you want to incorporate a load current, feed forwarding current mode control K p, K i, s. And we have already discussed in lecture number 50 all these derivations in detail. So, we are not going to repeat it for step up and step down, integral gain computation and normalized gain.

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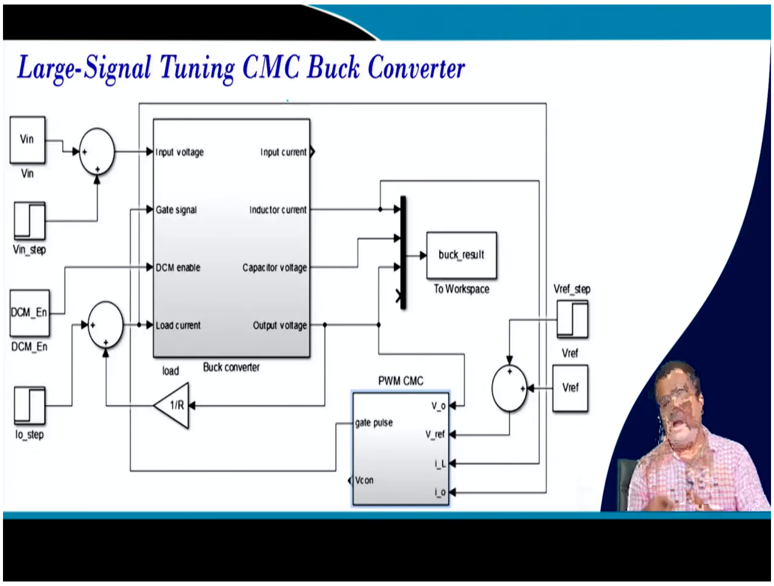

And we know already how to implement current mode control.

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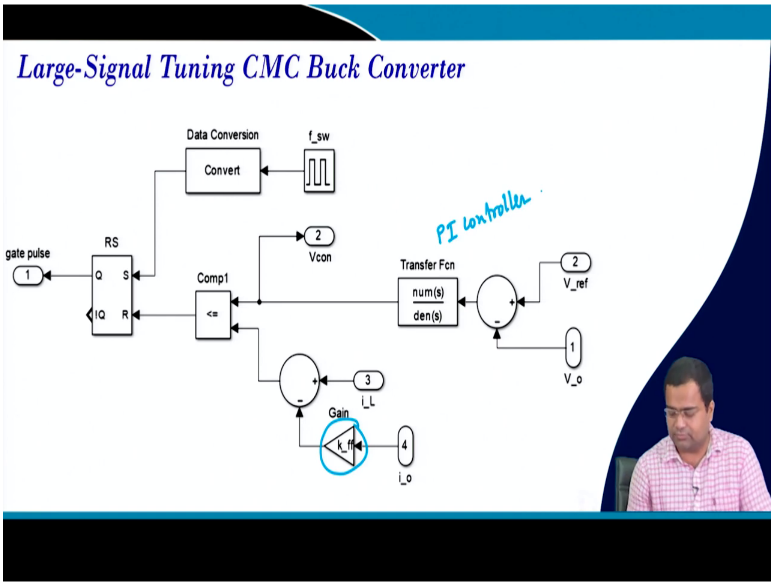

Here this feed forward gain is inserted for the tuning purpose. And here we are considering PI controller for large-signal tuning that we have discussed.

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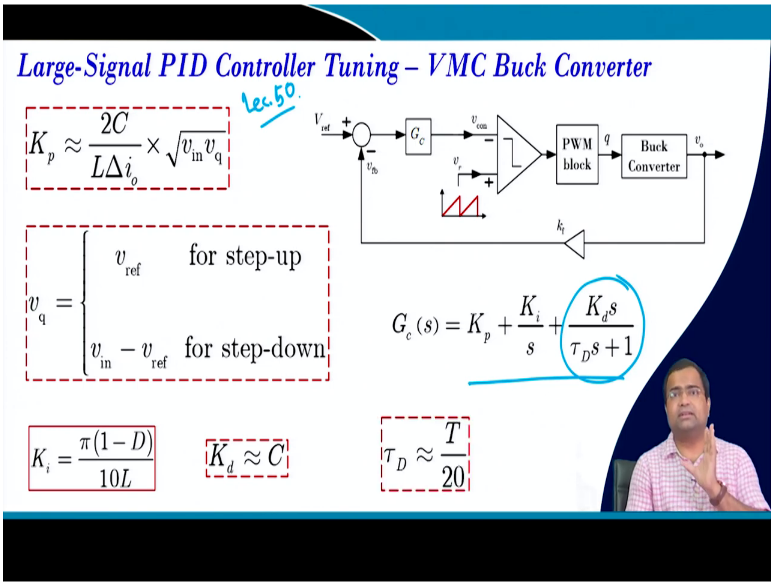

And we can apply the large-signal tuning for voltage mode control, where we have considered a PID controller with a band limited derivative, right? And we already discussed in lecture number you know 50, regarding all these parameters of this q and K i and derivative gain as well as the time constant of the band limited derivative.

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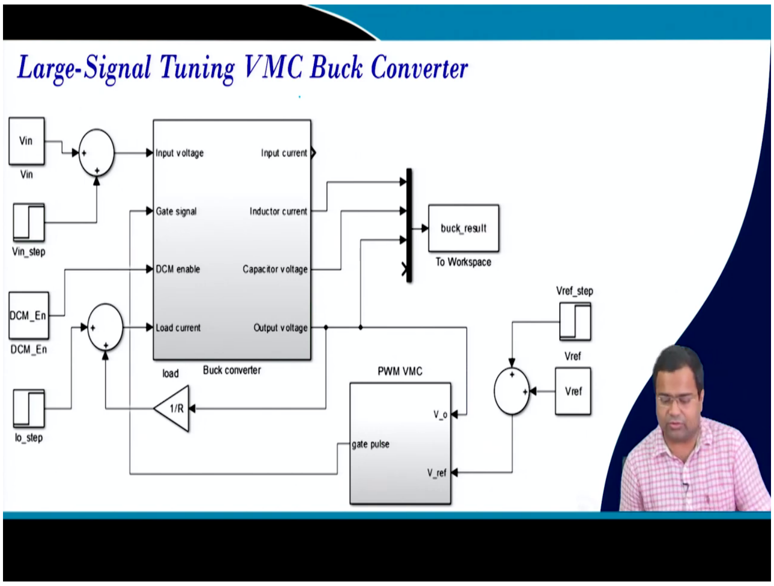

And the large-signal tuning voltage mode control, it is a standard voltage mode controller, nothing special.

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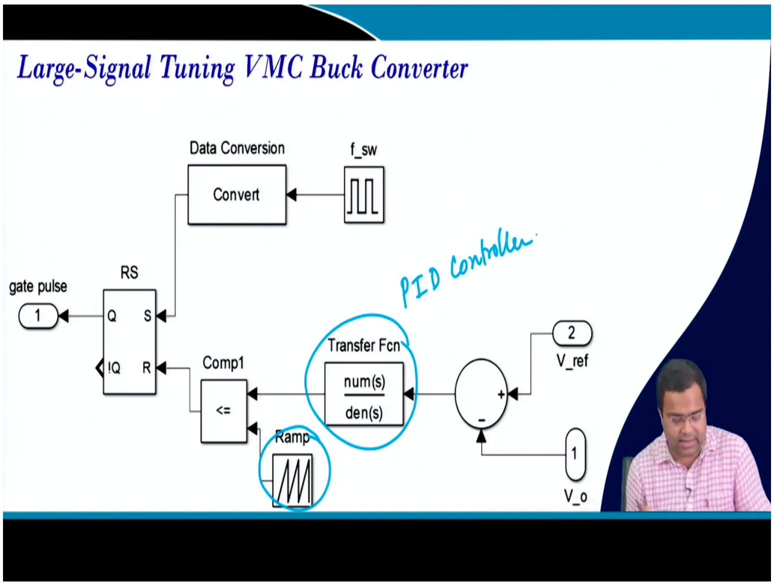

You can add a sawtooth ramp and this controller we are taking like a PID controller, PID controller with a band limited derivative. And the gains are accordingly set, according to our you know formula, right? Now, we are going for MATLAB implementation.

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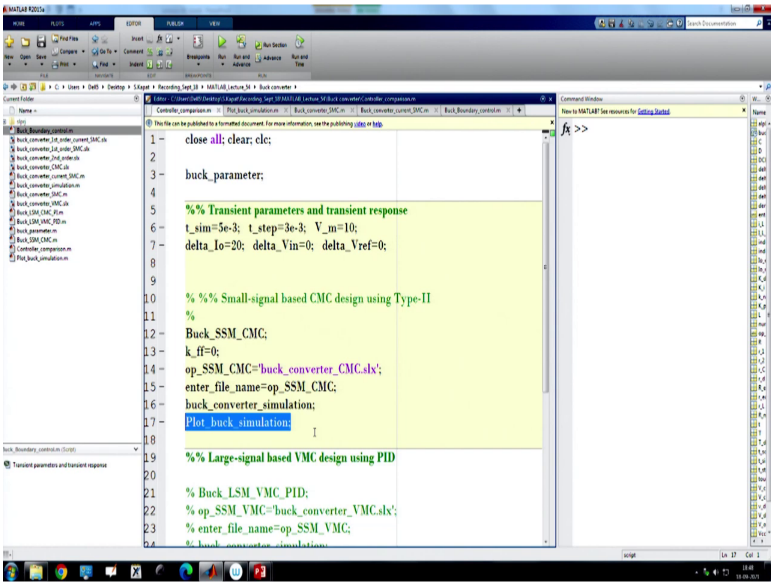

So, in MATLAB, we are first going to take one by one. So, first let us say, we want to take the performance of the regular current mode control because we have a small-signal based design.

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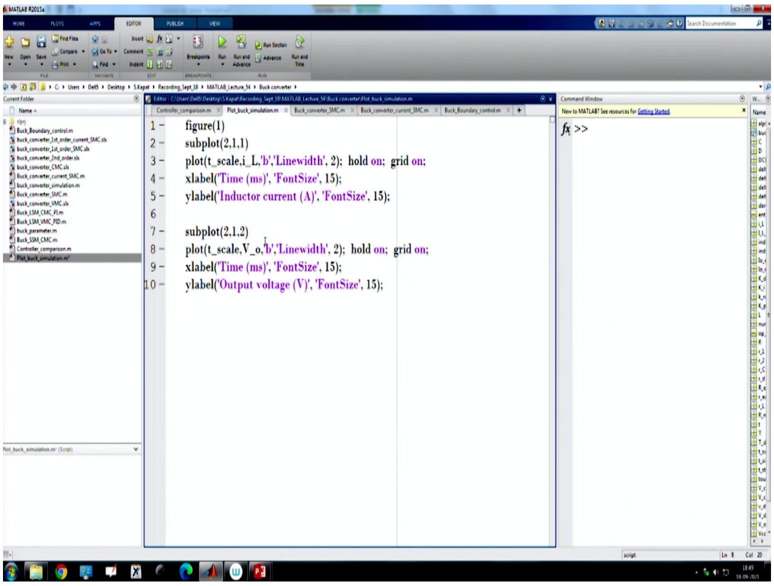

And we want to check the performance, let us say for the if we use a blue color trace, blue color, these are small-signal based current mode control.

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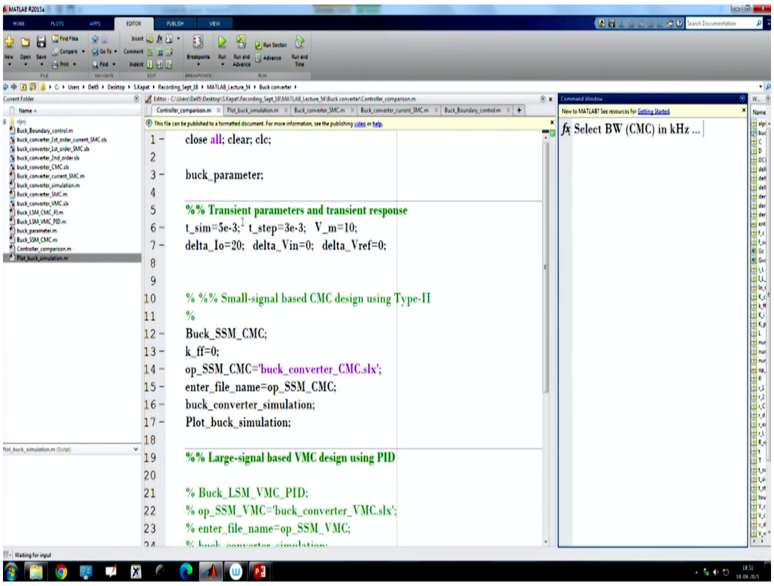

Here, we are first running current mode control, where we have considered one eighth of the switching frequency because of the model validity we have checked.

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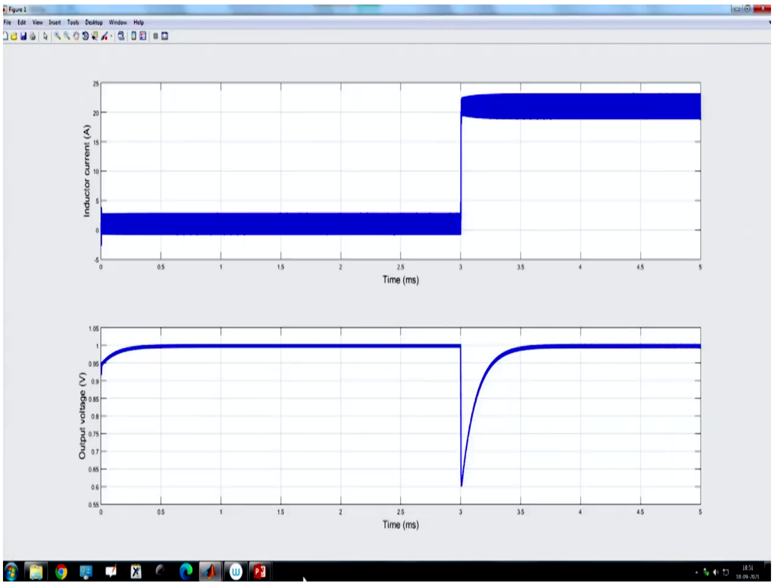

So, this is using our current mode control, ok.

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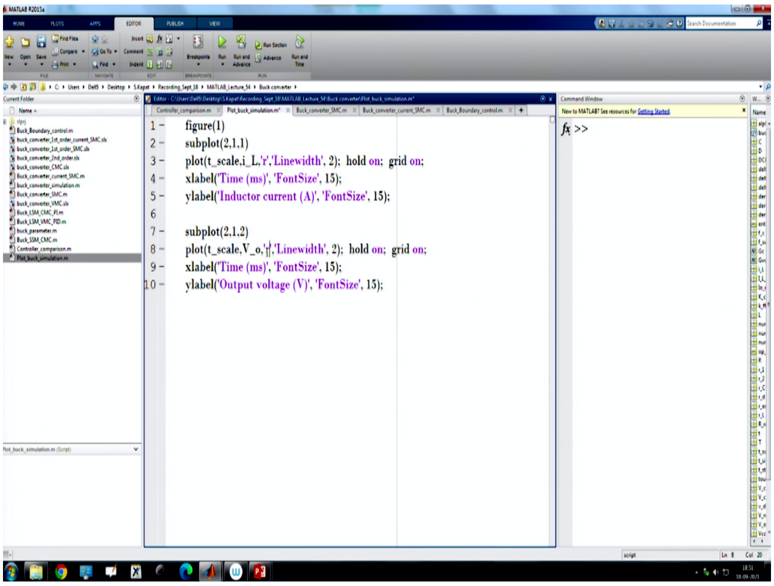

Now, on top of that we want to plot our response using large-signal based current mode control and we want to comment it, ok.

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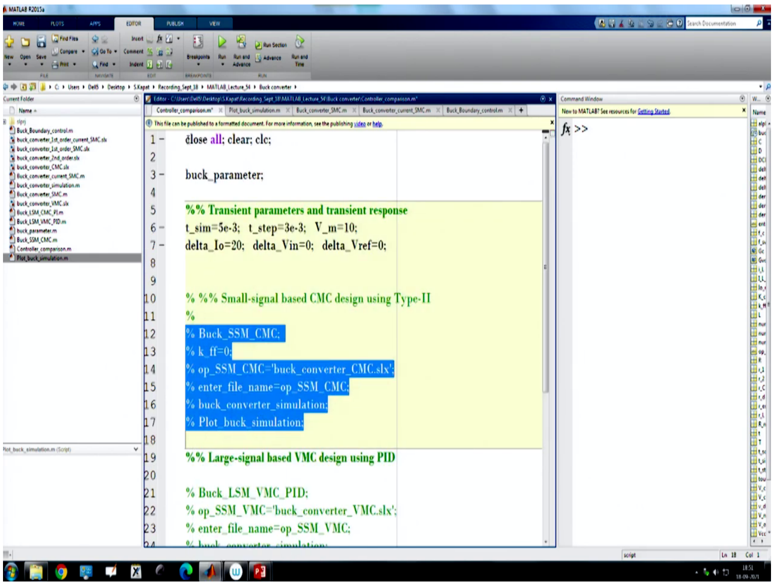

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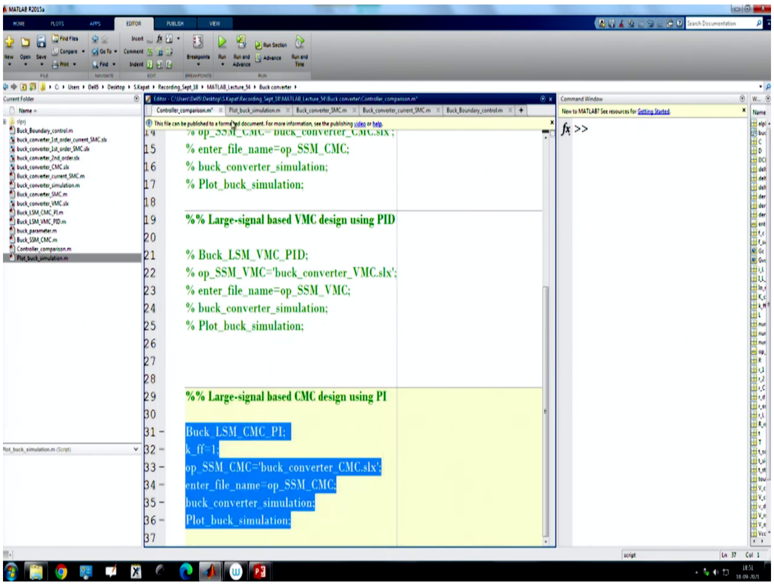

And we want to enable this large-signal based tuning.

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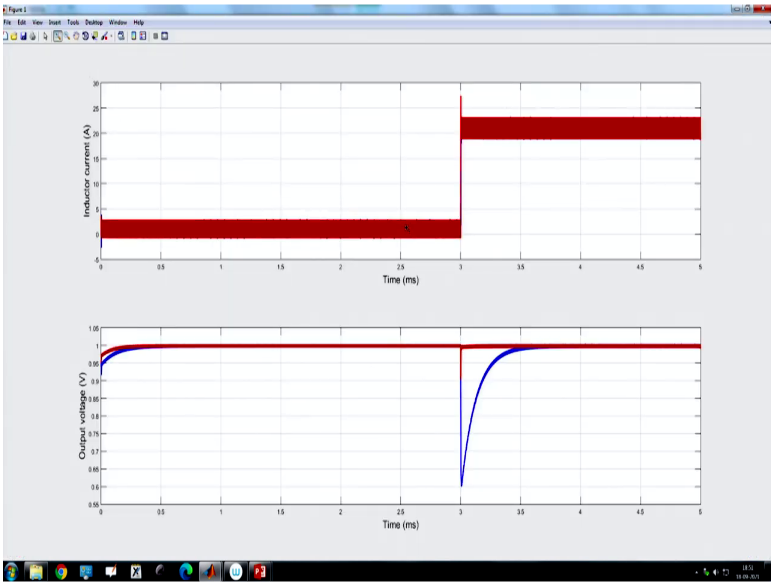

So, you will find because large-signal based tuning almost achieve, very fast transient response, almost close to the optimal condition in one switching action, more or less, ok.

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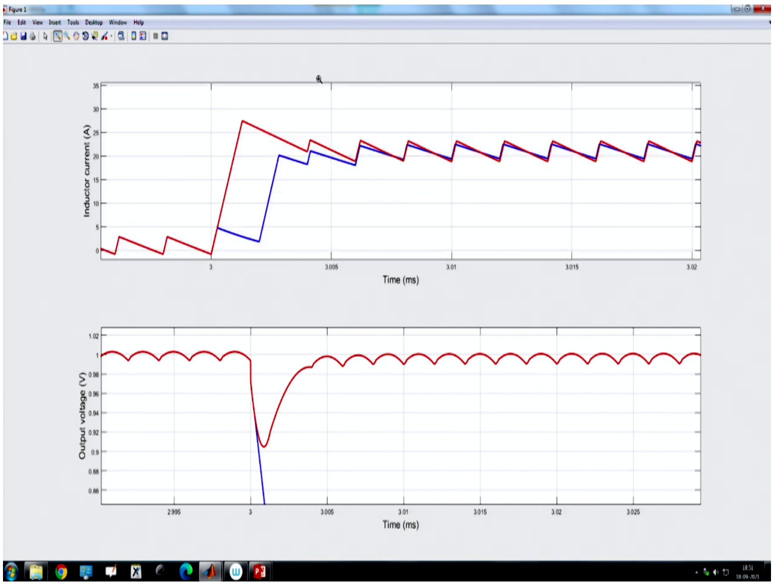

So, you can achieve very fast transient response.

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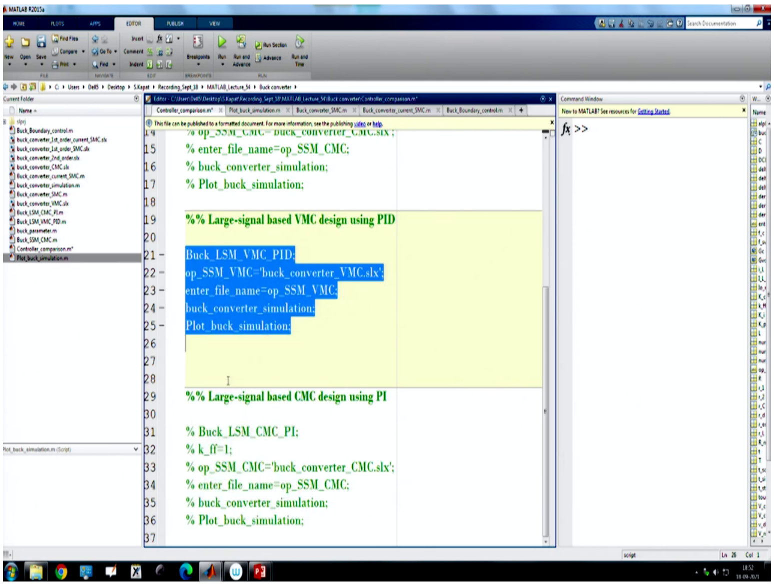

Now, we want to check the voltage mode control along with this. So, you can comment on it. And if you go for voltage mode control, we want to change using a green color.

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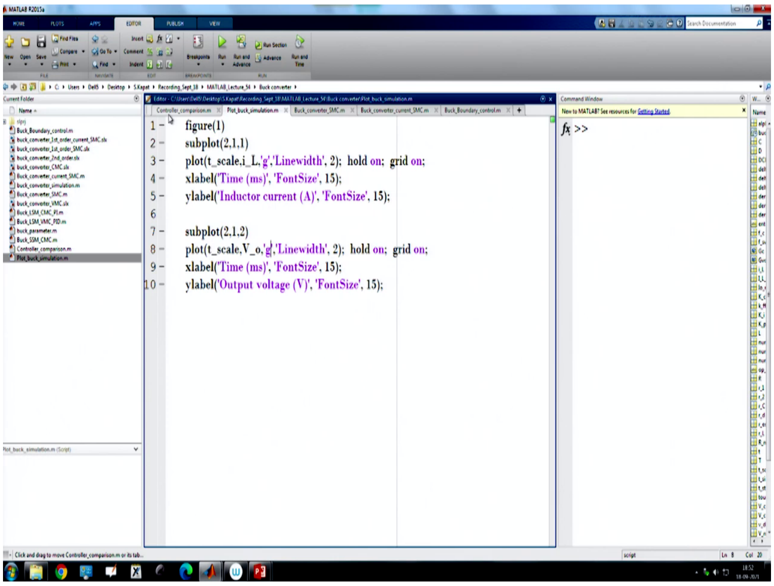

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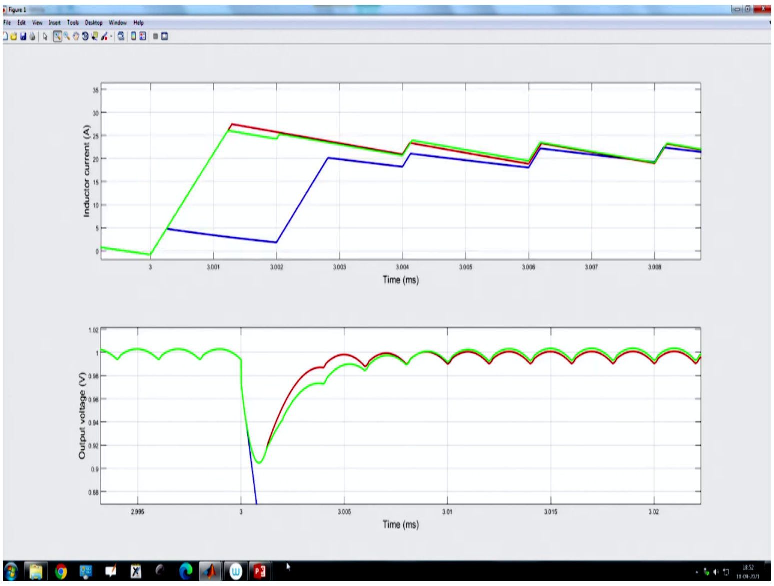

And you will find that the response in voltage mode control is also close to time optimal, but there is a slight you know variation because maybe we have taken a large ramp. But it is much faster than you know the traditional voltage mode as well as current mode control. We are not showing voltage mode because we have shown that voltage mode control will also generate overshoot undershoot in case of type-III compensator, ok.

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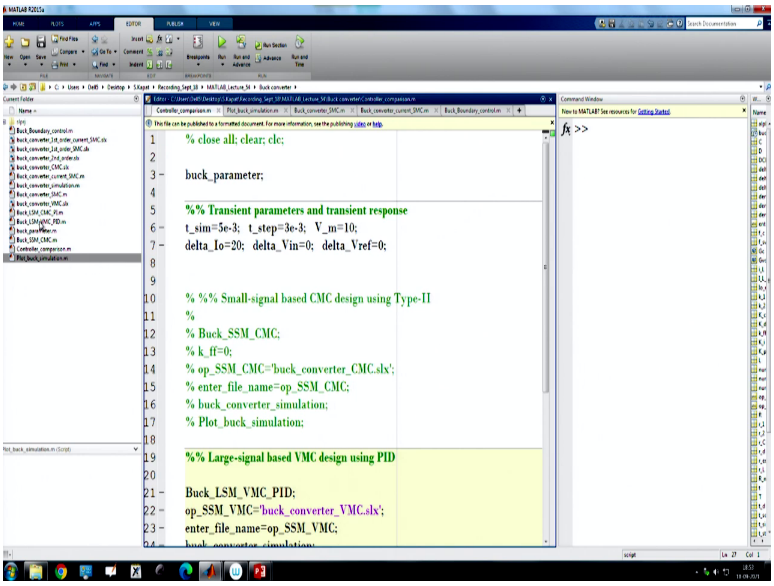

Now, we want to compare, ok. So, we want to compare our performance.

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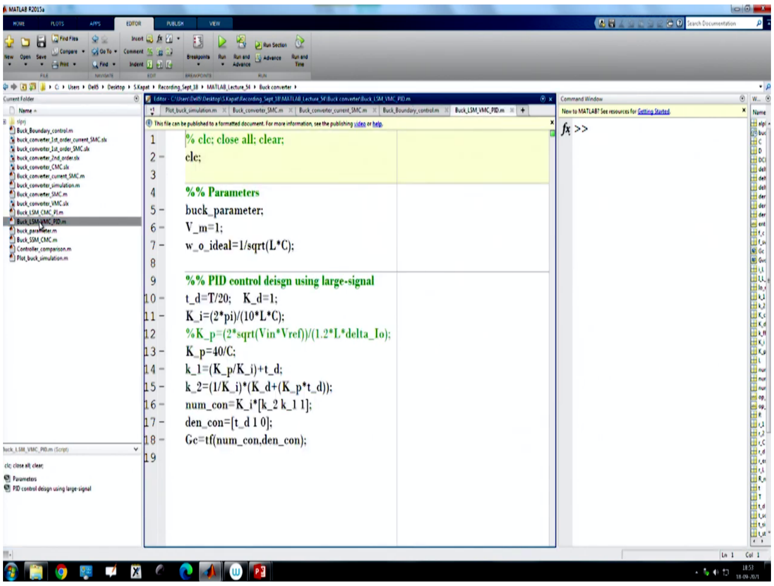

So, if you go to voltage mode control large-signal V m, yeah, we have chosen this. So, now, we want to show the nonlinear controller, so, that means, you know how nonlinear controller. So, on top of that, let us go to our voltage based sliding mode control, voltage based sliding mode control, again we are considering load step transient, same load step transient 20 ampere.

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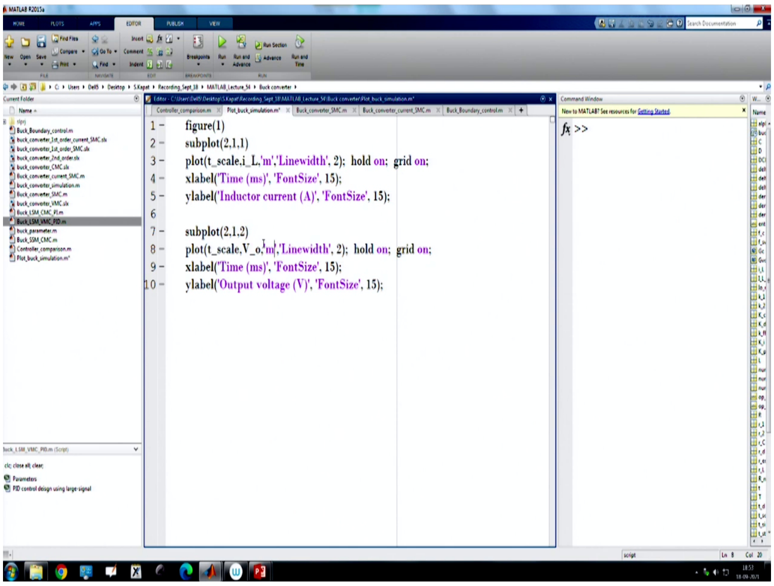

Now, we want to plot using a different color. So, let us say we are going to use in magenta color, using voltage based sliding mode control.

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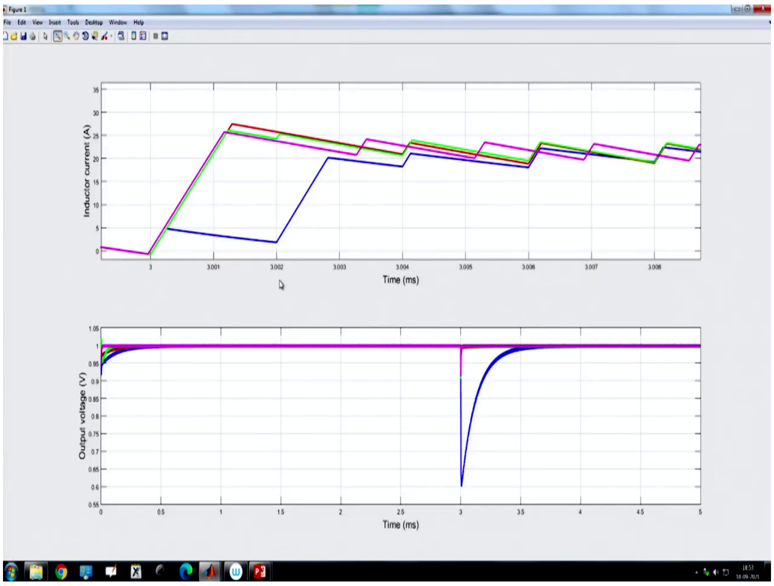

So, if we run it, voltage based sliding mode control that we have discussed, you see this also achieve very fast response, magenta color.

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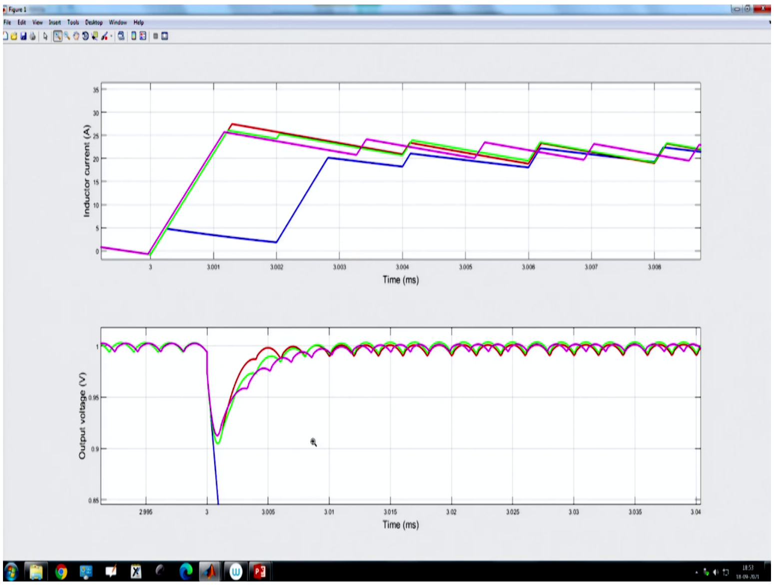

At least it is much better than our traditional current mode control, ok, so voltage based.

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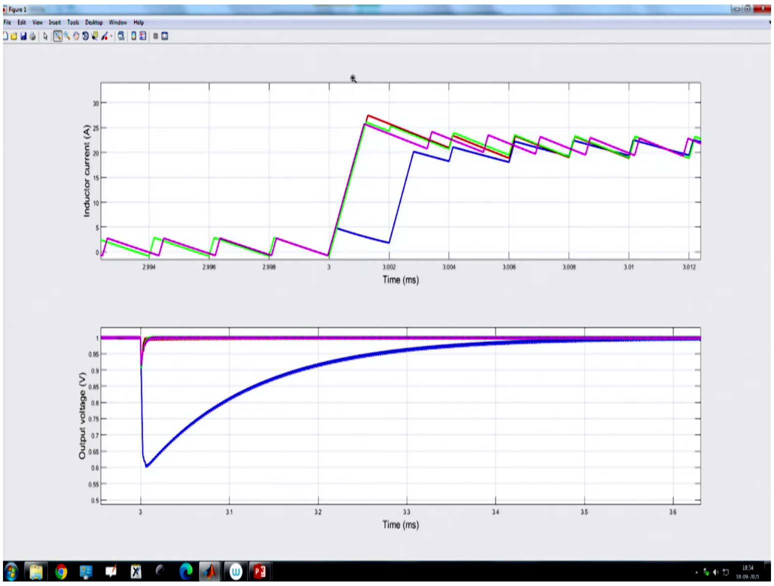

Now, we can play with the switching surface. And you see there is a variation in the switching frequency in voltages because we know the voltage. We do not choose the right amount of threshold or very hysteresis band, then it may lead to variable frequency the switching frequency will deviate. And that is clear from the magenta color. You see, it is not exactly common. Whereas, the large-signal tuning and the regular control, they are overlapped at steady state, ok. But you know this variable frequency is there in a sliding mode control.

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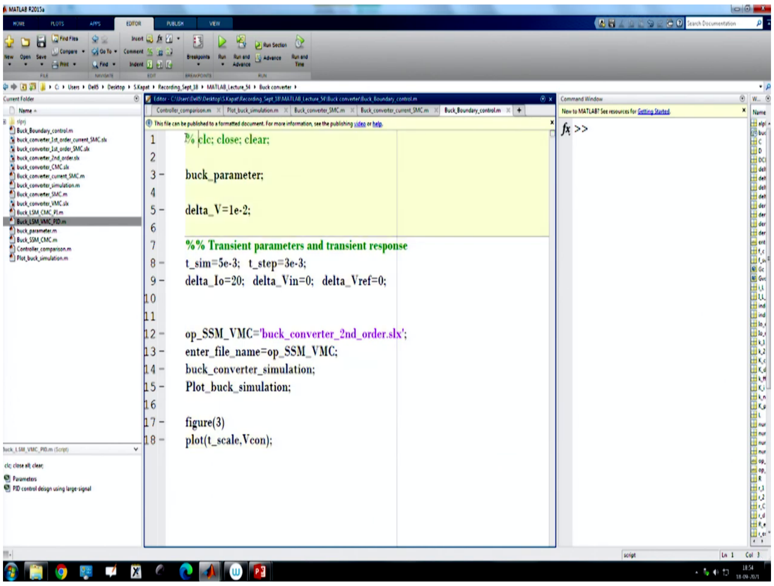

Next, we want to compare we can do very; so, on top of that we want to go for boundary control, where the second order switching surface.

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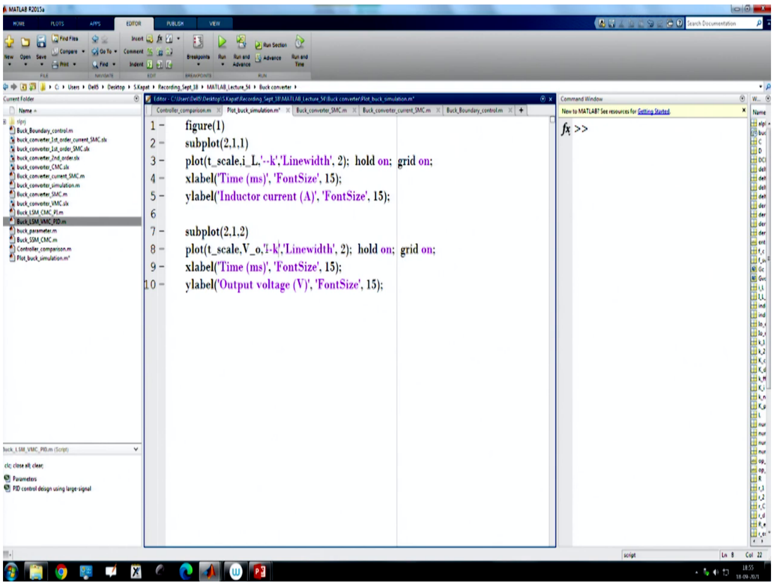

And we want to use another color, let us say we want to use black color. So, dotted line black color, and let us run it, boundary control, and see what happen.

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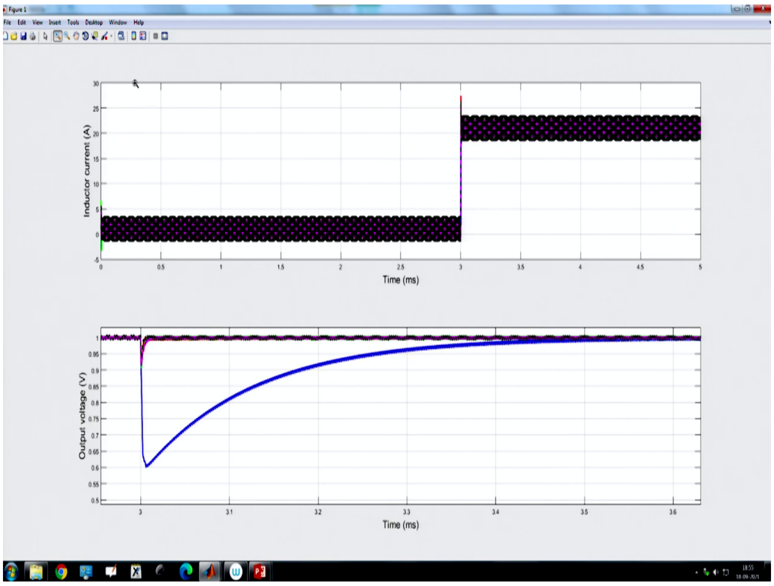

So, this black color is the boundary control.

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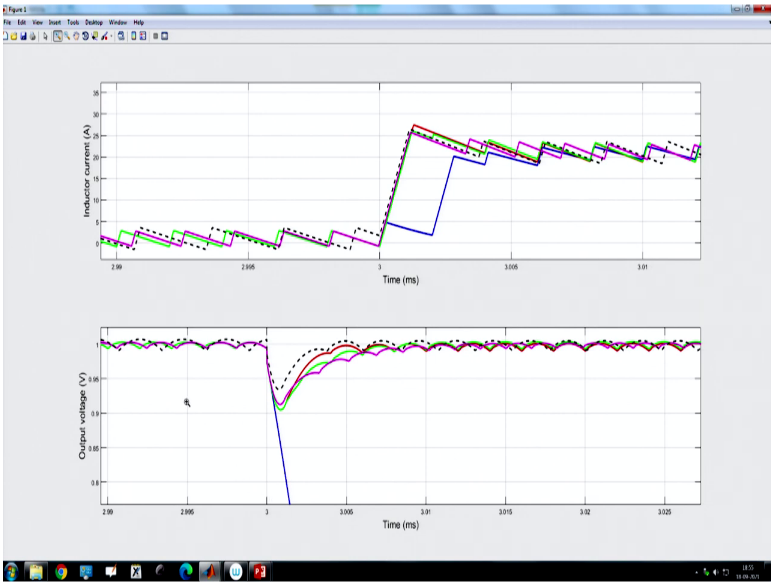

That means, if you go back, so this is also a kind of optimal response, very fast transient response.

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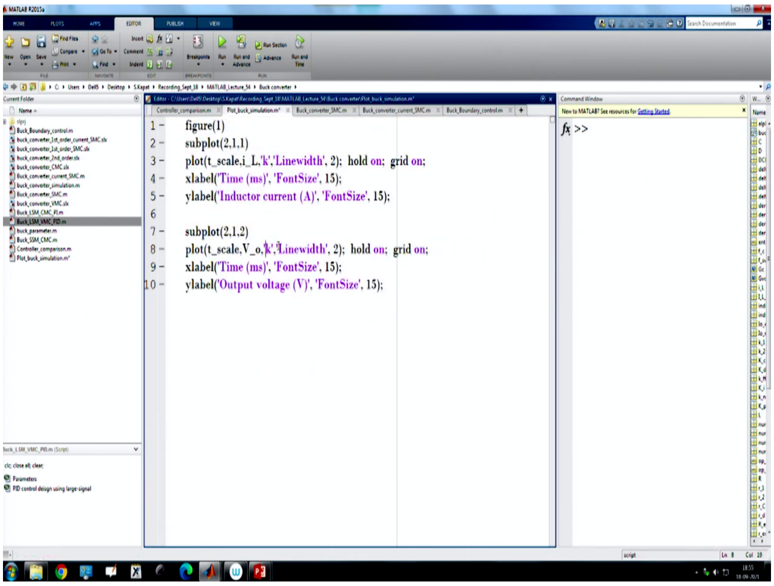

So, I think instead of black, let us use you know dash, yes.

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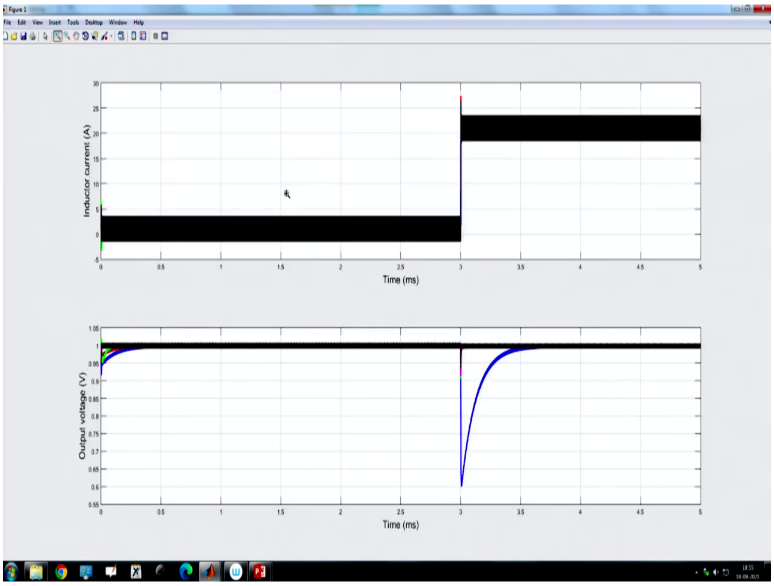

So, you can see, here also there is a problem like difficulty in the switching frequency variation.

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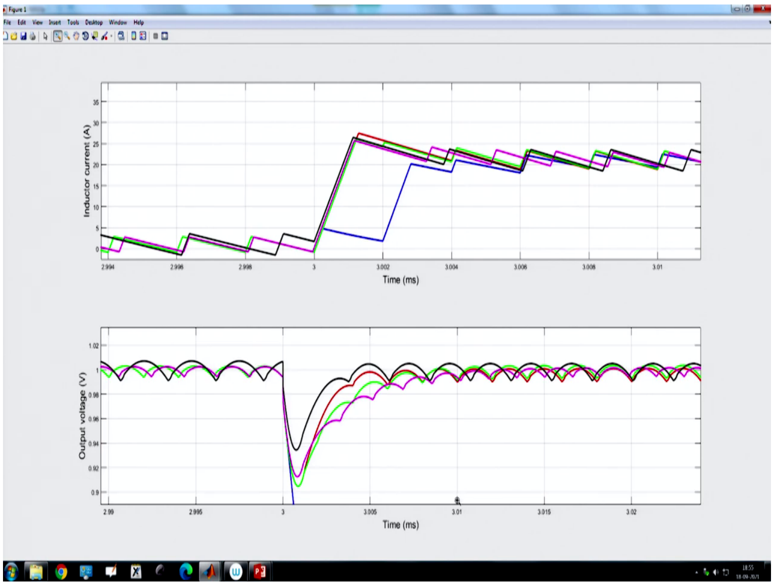

So, you have to set the right band, but the response is very fast you know, kind of very fast and you can get close to optimal behaviour, time optimal, it is close to time optimal behaviour.

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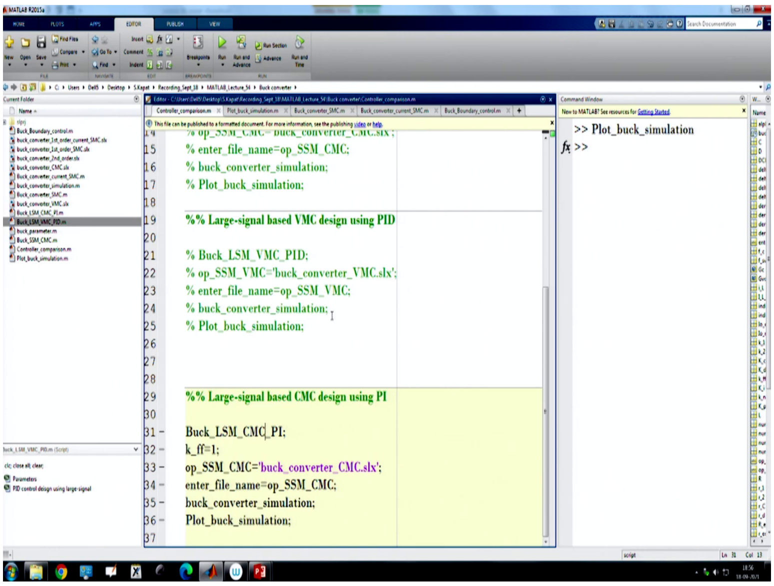

So, if I want to compare this, you know I want to compare the large-signal tuning of the current mode control; that means, if I go, because I want to show the nonlinear control versus nonlinear tuning, ok; because that is the.

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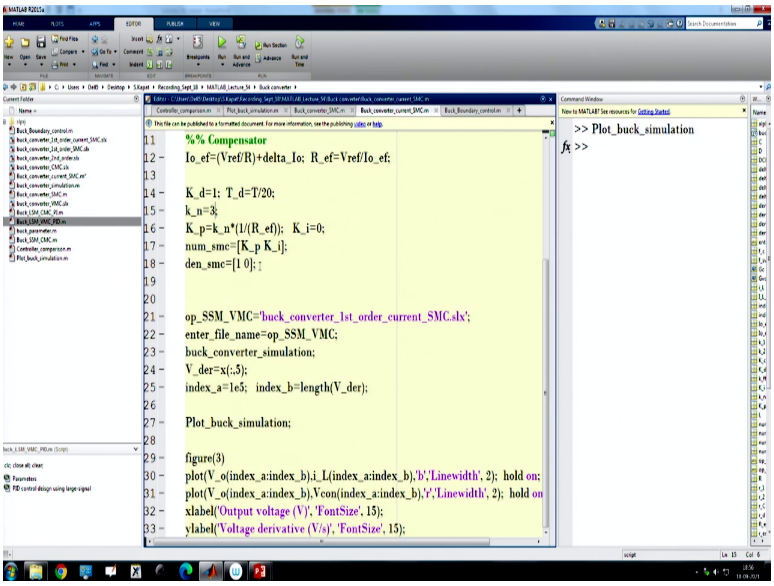

And another thing, I want to I forget to show that if you go for current based implementation; that means, if you go for current based implementation, so we will do all together.

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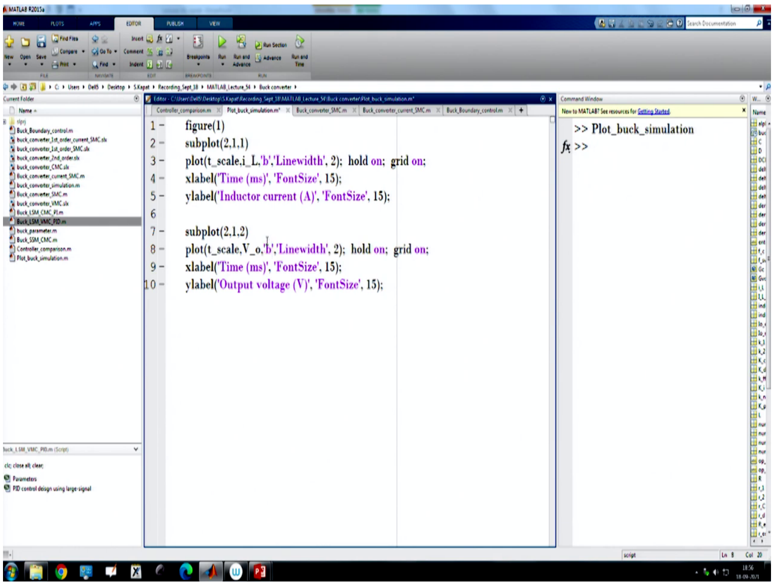

First, we will compare our plot using blue color; blue color is the nonlinear tuning.

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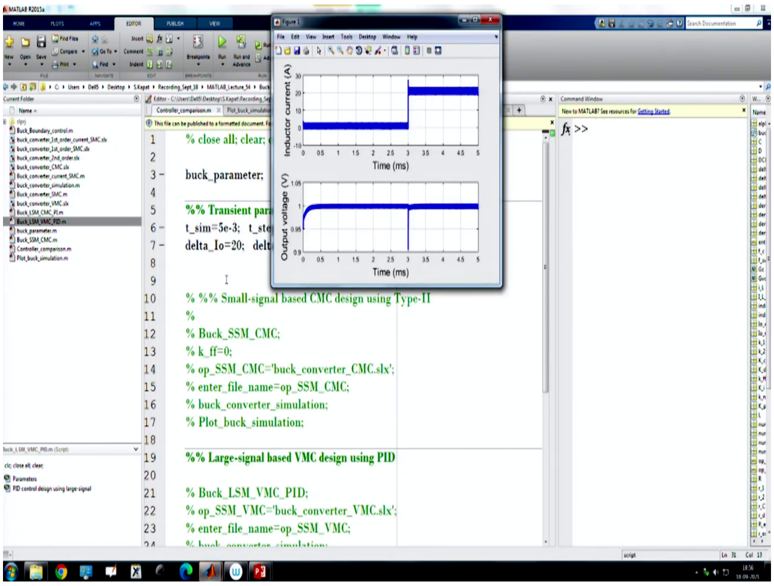

So, this is our nonlinear tuning, ok.

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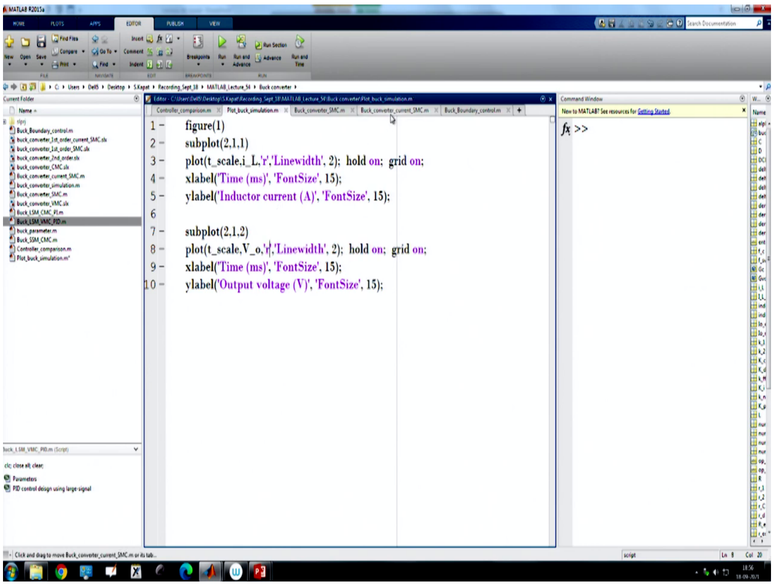

Then, we will go for current based sliding mode control which we are going to use a red color.

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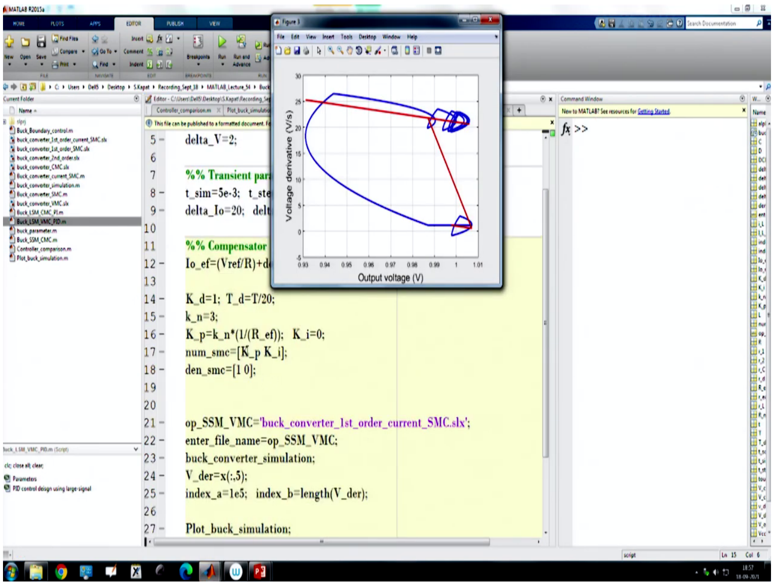

That we are going to repeat on this.

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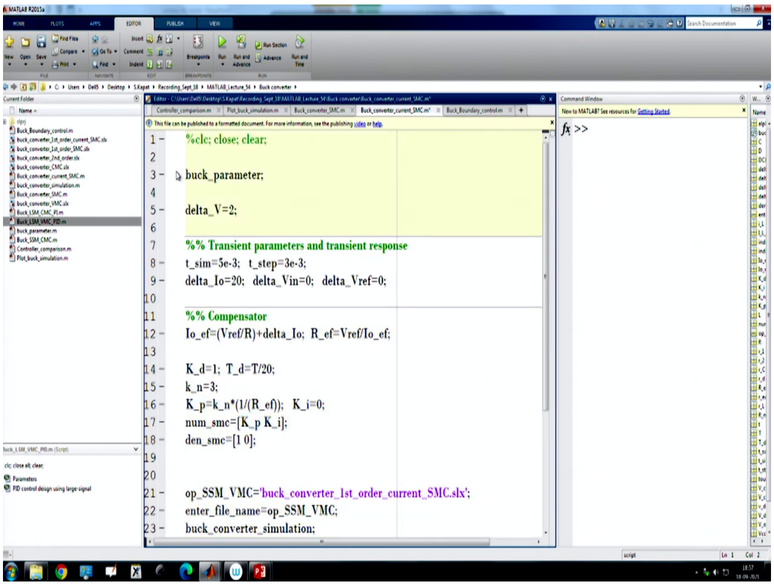

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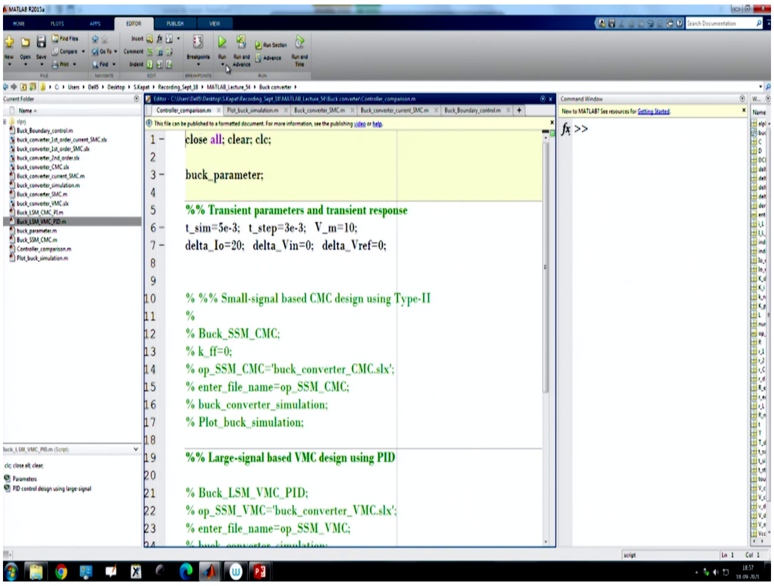

I think we have erased the earlier one. So, that was the problem, ok.

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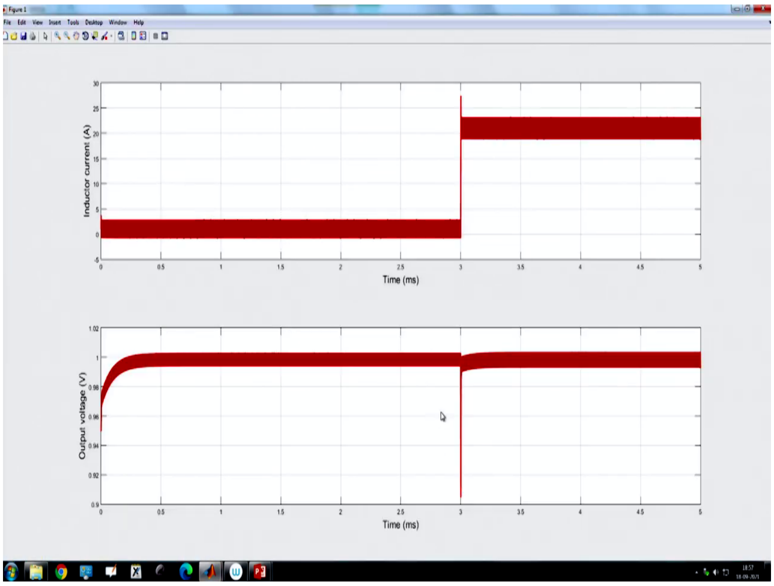

So, again, we start. So, here we are using red color is the large-signal tuning. Large-signal tuning is a red color.

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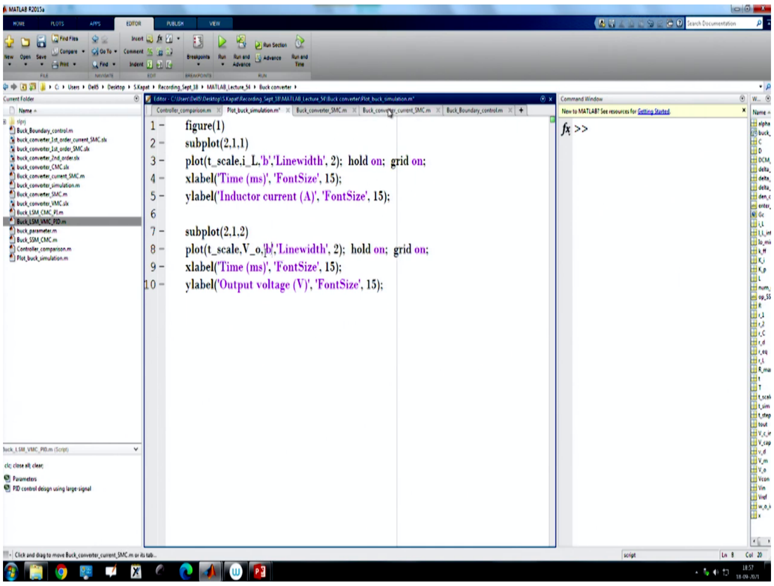

Then, blue color is the current based sliding mode control, first order switching surface; current based sliding mode control, this is the blue color, the blue color, ok.

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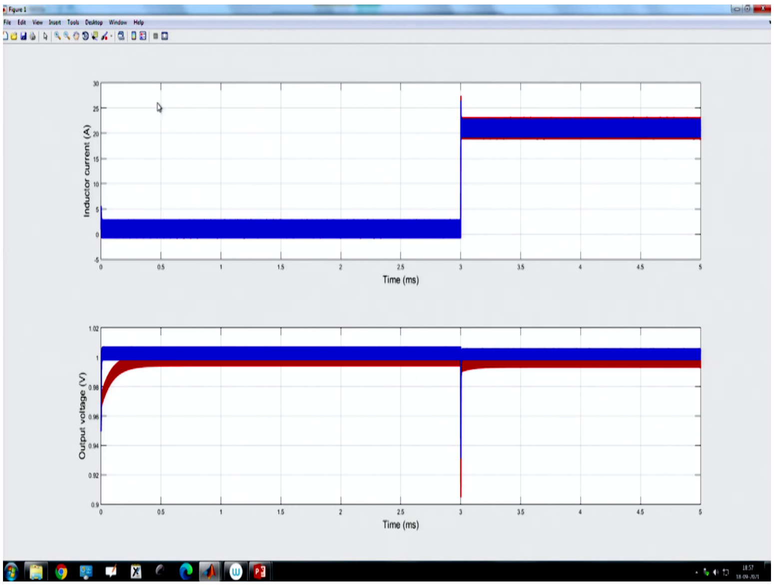

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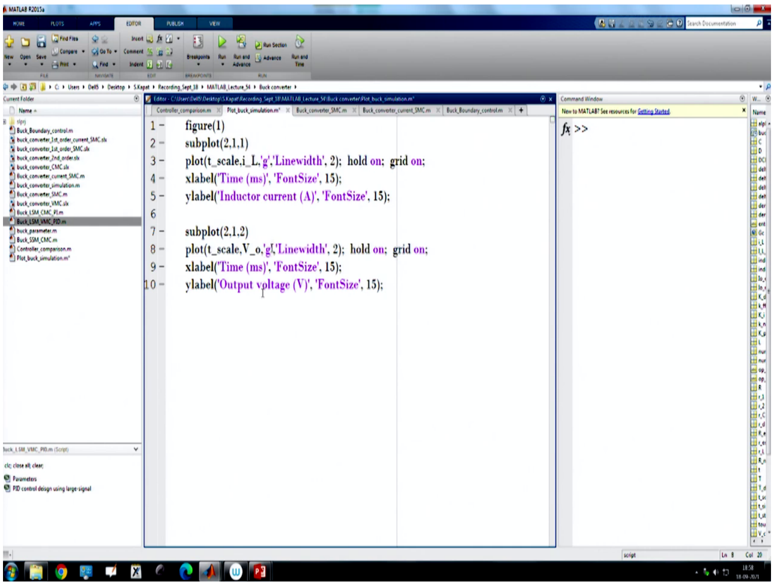

And you can see if you go close, it is also very fast. Go for green color, the second order switching surface, ok. And you want to see how does it looks like.

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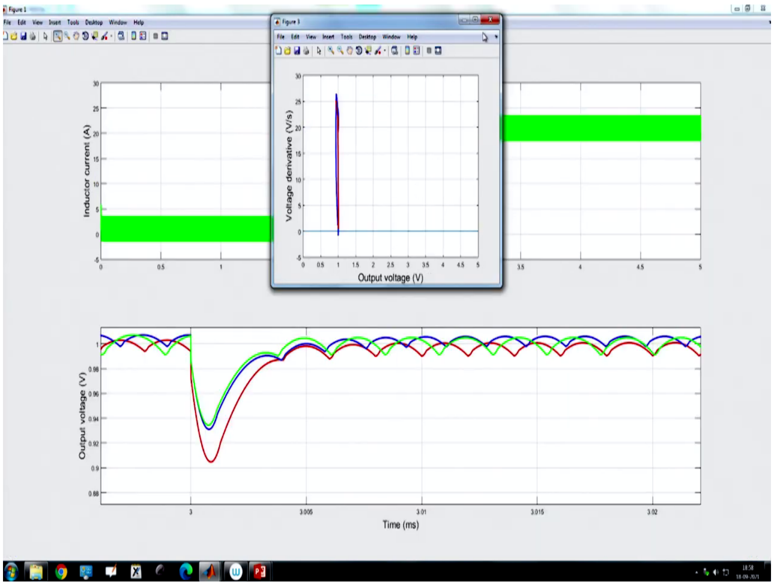

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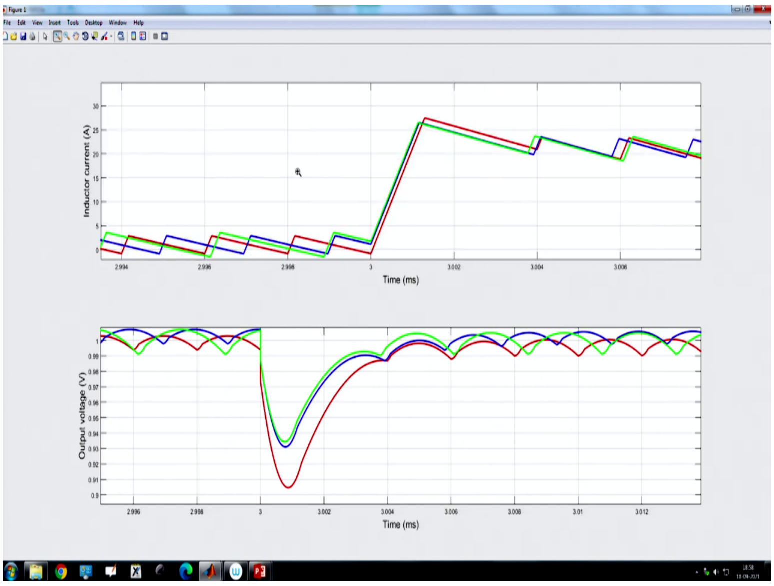

So, the second order switching surface is also going close to this, and this also gives optimal recovery. That means the large-signal tuning and practically the current based sliding mode control we have designed using our large-signal tuning. That is why they are happening almost in optimal recovery time. But only due to the shift of this voltage, average voltage, so that is why there is a shift in the output.

So, that means, the nonlinear control and where we are using current based sliding mode control, where we are using you know for the current based sliding mode controller using first order switching surface, and that switching surface slope is derived from the optimal criteria, ok. So, this additional undershoot is coming here due to you know because even if you go for example, just a minute, yeah.

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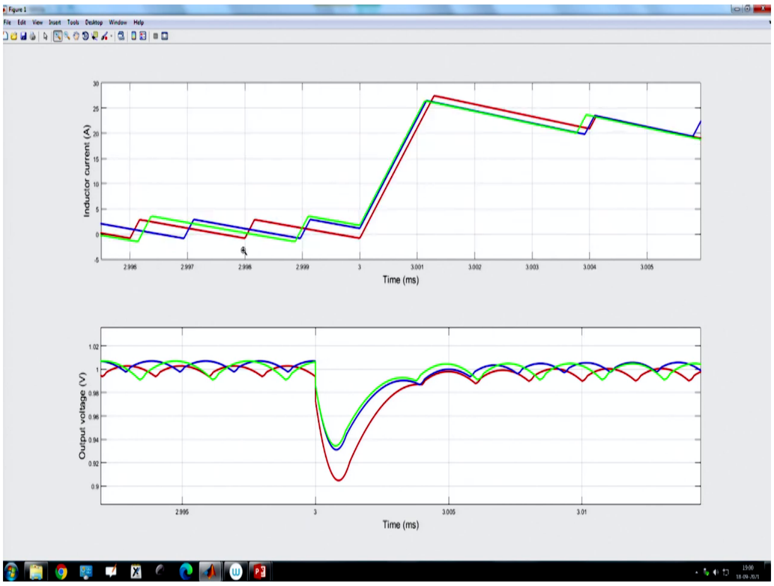

So, because there can be a slight delay in the PWM based control that we did because the modulator delay, but in case of switching surface based hysteresis, like you know sliding surface based design, there will be no delay it will respond because it is a hysteresis control, ok.

But, that if we can apply our tuning rule for first order switching surface and get the optimal slope, and if we apply the same thing for regular current mode control, then we will get almost time optimal recovery which is possible using second order switching surface. Now, we have to go for boost converter. So, that means, we have compared all these results. Now we will go for a boost converter for a comparative case study.

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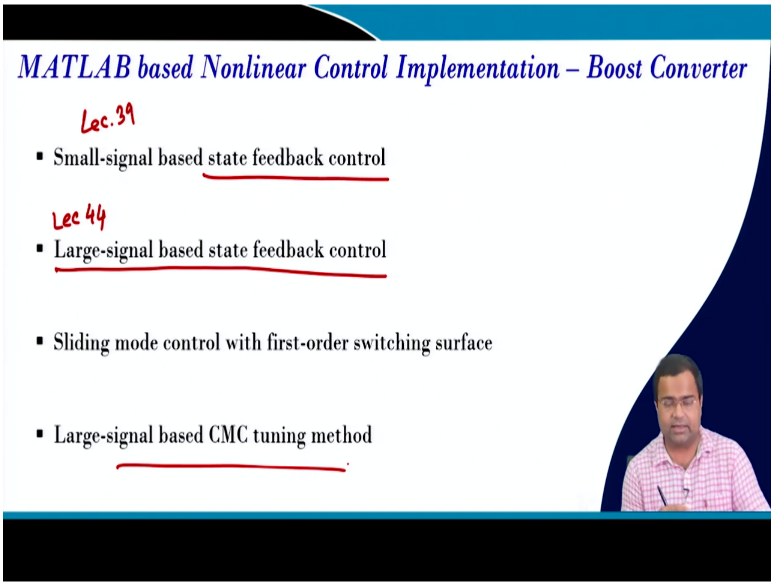

So, now, we are going to discuss the boost converter MATLAB case studies. In this control technique, we have considered in a boost converter you know state feedback control where we have used both small-signal as well as the large-signal based design because you know in lecture number 44. So, these two in lecture 44 and this in lecture 39 the state feedback design we have considered.

So, 44, we have used a Lyapunov criteria to show because you know beyond certain bandwidth your model validity is a constant. So, small-signal model is no longer is used, useful. But if you use a Lyapunov criteria, you can still go further, so that your system you know stability can be defined in for even for a large duty ratio variation.

And then we will discuss sliding mode control with first order switching surface where we have computed the slope of the switching surface by optimal gain. And then we will consider the large single based current mode control tuning, and we will also show current mode control tuning using small-signal based design, comparison with MATLAB case study.

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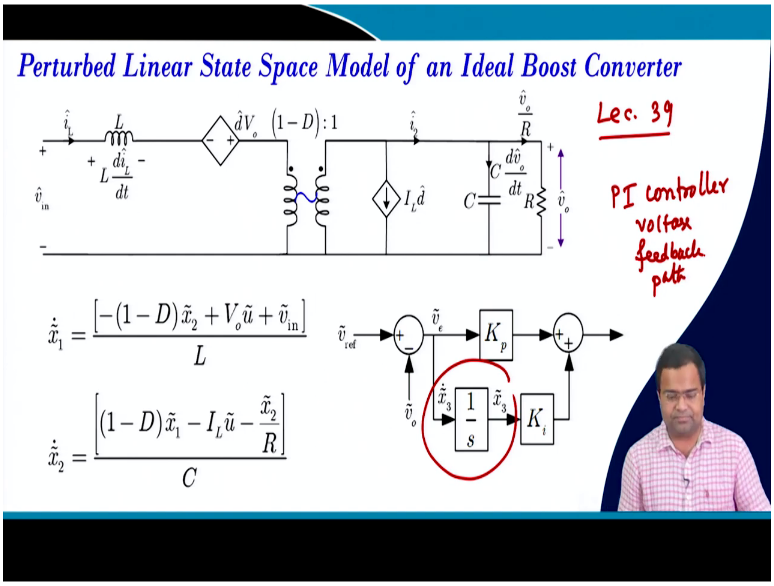

So, first if we recall you know lecture number, I think 39. We have discussed this perturbed model how to obtain the perturbed state space model of a boost converter, an ideal boost converter.

And then, we can incorporate the integral gain because we are using a PI controller in the voltage loop, and it is a state feedback control, current loop is there, like a current feedback is there in the voltage controller using PI controller in the voltage feedback path, voltage feedback path, ok.

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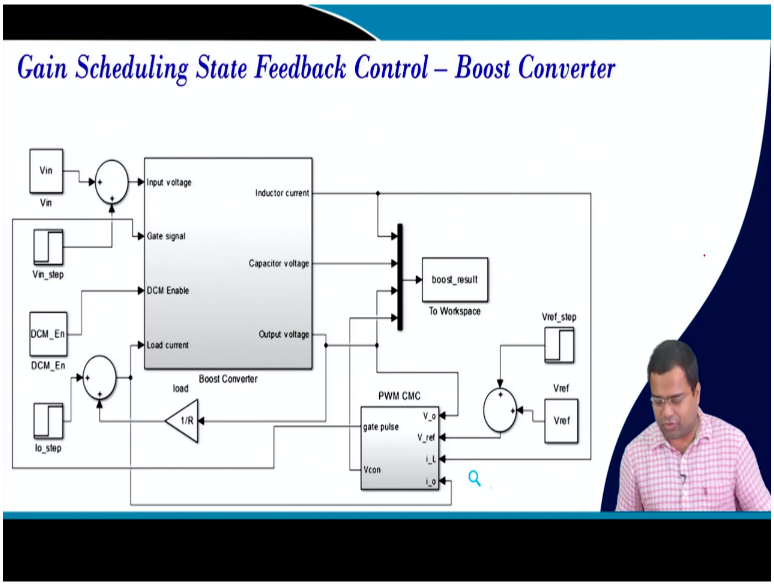

So, now if you go for state feedback control and where we are also considering load current feed forward.

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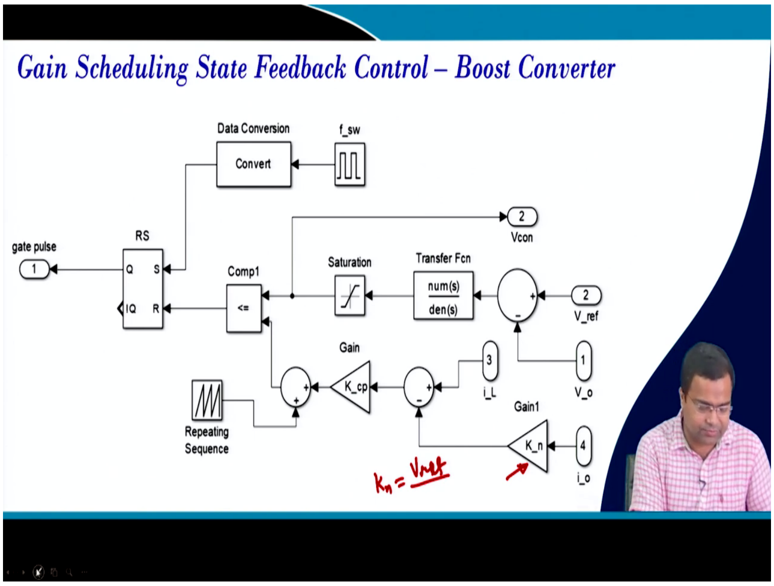

But, if you set K n to be 0, then there is no load current feed forward or if you set K n to be V ref by V in, ok; just if we set.

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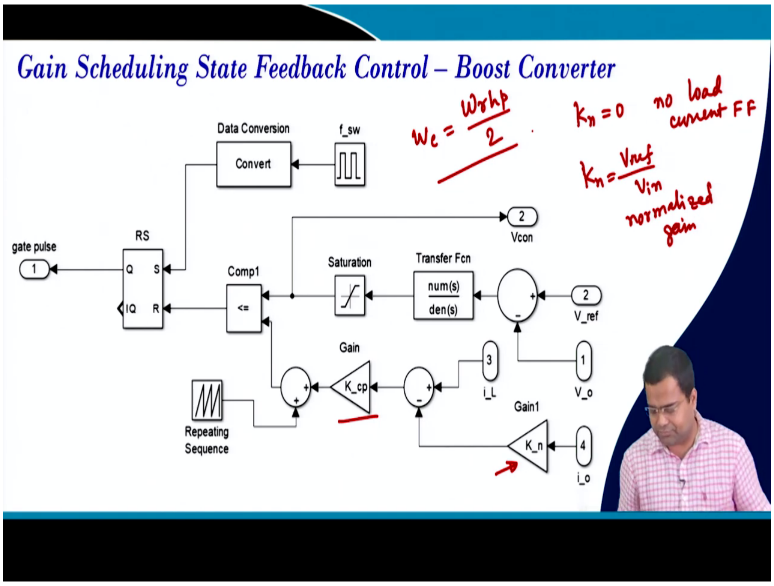

That means, if we set K n to be 0, no load current feed forward, but if we set K n to be V ref by V in, that is the normalized gain. Because you want to normalize the load current to take that with respect to the average inductor current, ok.

And here we are also using a gain for the current loop, but you may add a ramp because if you find some stability issue because we are talking about state feedback control, where the whole control logic there will be a modulator gain, the whole after summing up you will have to have a comparator. So, because even modulator should be there, so this sawtooth waveform is acting like a modulator.

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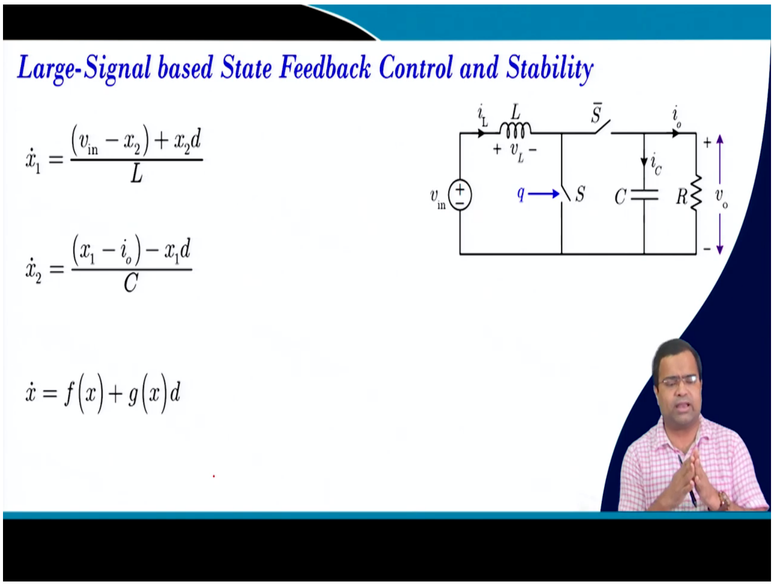

So, we have discussed; and now if you go for large-signal based stability criteria because small-signal based design we can use to obtain closed-loop poles eigenvalues and then we can decide the about stability. But the model validity was concerned because of perturbation and duty ratio. So, here we can we will go up to the crossover frequency, omega rhp by 2, that is our time. beyond that the model is not at all useful.

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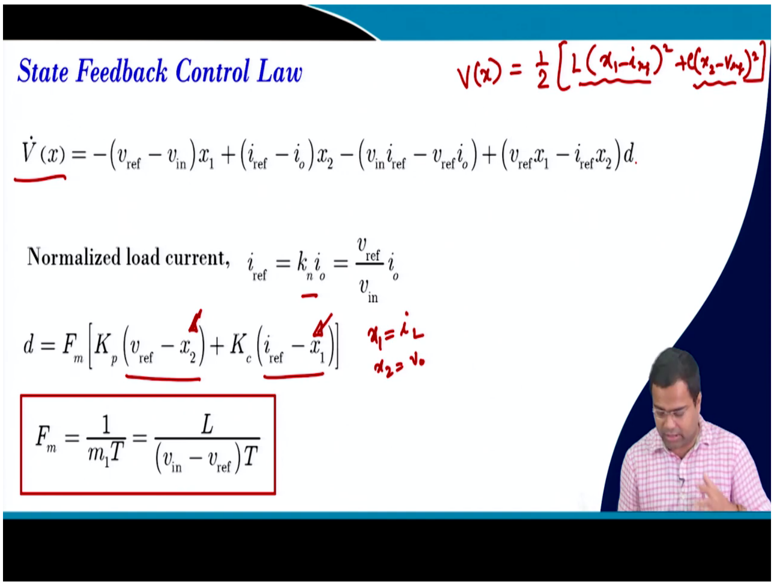

But, in, if we go for large-signal based state feedback control and we want to see in this case the state feedback control law, it consists of you know the normalized load current and also, the control law error voltage, x 2 is my output voltage and the error current where x 1 is the inductor current. So, x 1 is my inductor current and x 2 it my output voltage.

In this control law, we have to ensure the derivative of the energy like function. And what was our energy like function? We took this to be L x 1 minus i ref square x 1 is our inductor current, x 1 is our inductor current plus x 2 minus v ref square into c. So, L, that means, it looks like a something like an energy. This is like an energy corresponding to the inductor, energy current to corresponding to the capacitor, ok.

And as long as you can satisfy the derivative of this energy like function is negative, then you can actually increase the gain. And here model validity is a large-signal model validity only you have to ensure the duty ratio should not saturate, ok. So, we will consider this.

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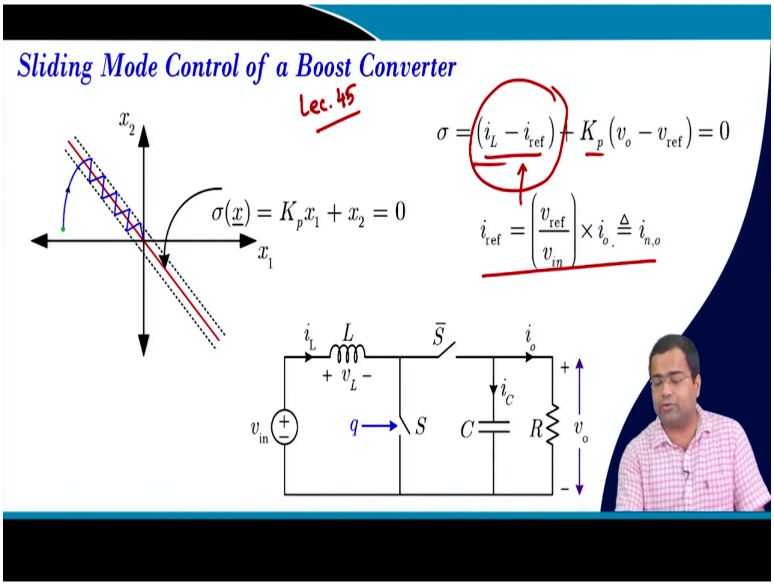

Then, the sliding mode control of a boost converter if we take a first order switching surface consisting of error current and the error voltage because in boost converter unlike in buck converter we should not consider the derivative of the output voltage to be another state. Because it can be shown that it exhibits non-minimum phase behaviour. So, the 0 dynamics will be unstable.

So, we should not use you know just a proportional voltage and the derivative of the output voltage. We can consider if we have to put a limit on the duty ratio because otherwise it may lead to unstable 0 dynamics and voltage will simply collapse and our inductor current will saturate. So, in boost converter, it is better to use the error current that is the best way to do. So, that you can also control the current.

And we have discussed some aspect of boost converter sliding mode basic concept in lecture number using vector diagram is lecture number 45, but not in design anything. So, here we are going to talk about boost converter sliding mode control.

And we have used this reference current to be normalized load current, which is v ref minus divided by v in into load current, ok. And if you go to implementation of this sliding mode control, I mean I will show you the MATLAB implementation of the sliding mode control.

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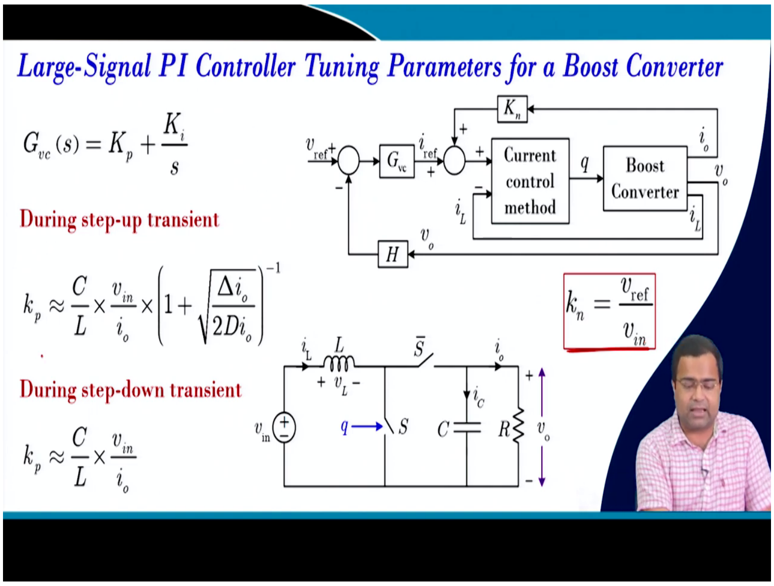

And then we have considered large-signal tuning of the boost converter where this K n is nothing but our normalized gain. So, what was our K n? Is v ref by v in, and these gains we have already discussed, right?

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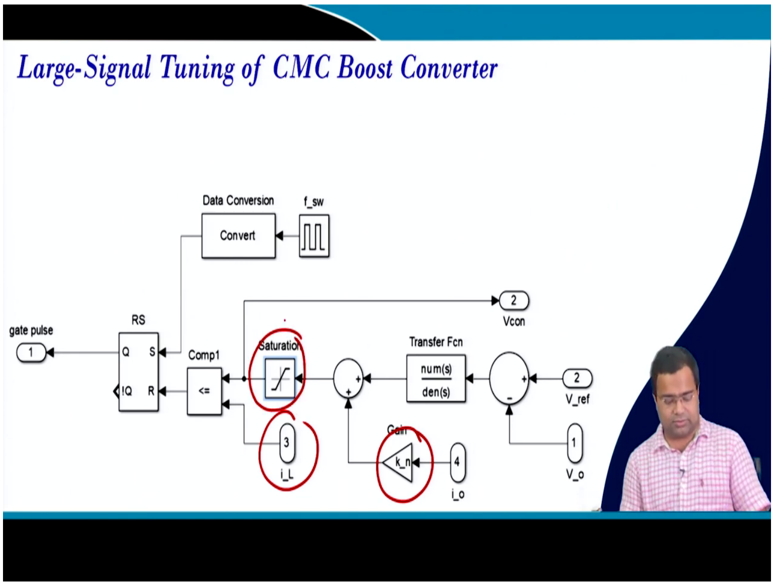

So, now, we are all set for large-signal tuning of boost converter. And let us go, we have also this normalized gain. The inductor current feedback is also there because I need to make sure the current reference should be in place, ok.

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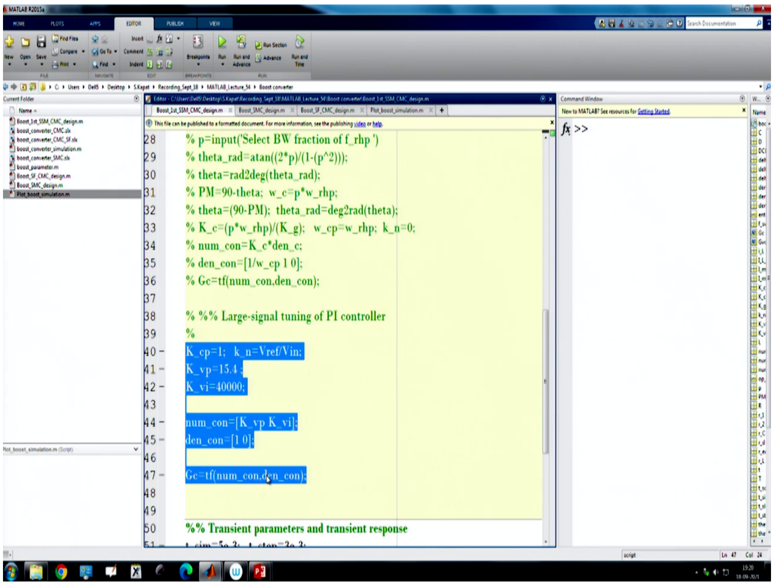

So, now, we are going for MATLAB simulation. So, first what we will do? We will run our regular current mode control.

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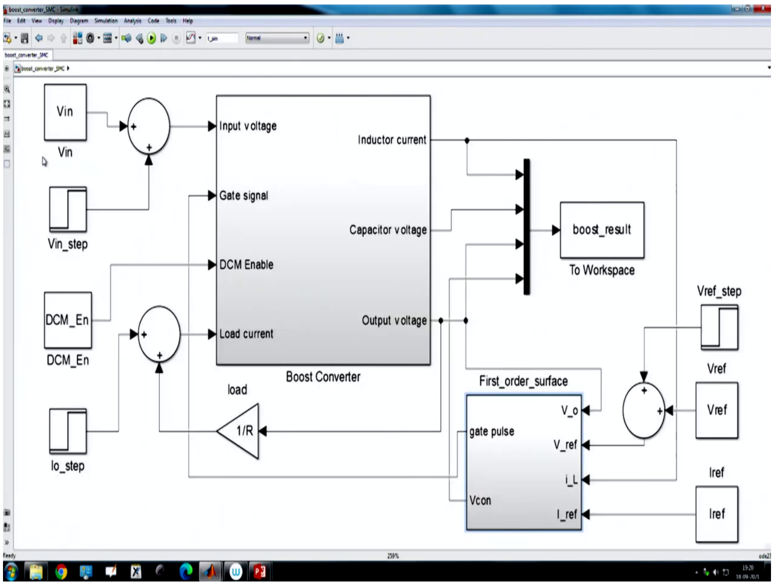

So, before that I want to discuss that if we go for sliding mode control implementation. So, sliding mode control implementation switch based. So, this is our sliding mode control implementation where the boost converter is common and that we have discussed in multiple times.

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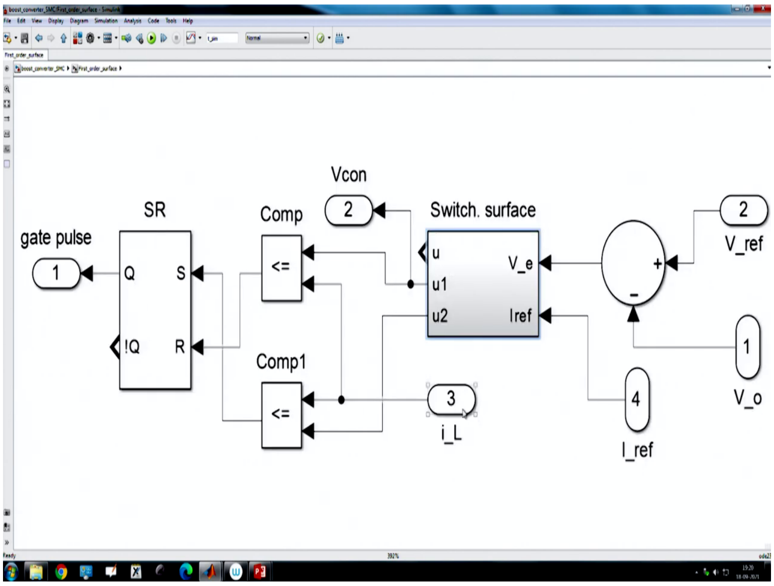

And this is our switching surface, you know, and if you go to the switching surface inside; it is taking error voltage, and the reference current is a normalized current.

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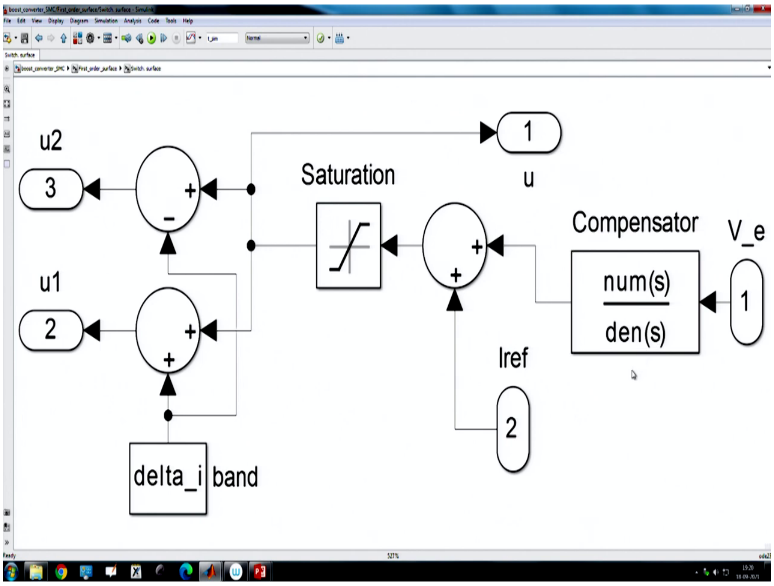

And if you go inside, then we have a controller here and it can be proportional controller. Even I will show you your PI controller can also work. But we will take proportional controller, then the reference current, and it is compared, this generates sigma 1, sigma 2, like current references.

So, here, only implementation is slightly different. Here we are generating current references, ok. And this is creating a hysteresis band and then we are giving the gate pulse. So, here if we since we are using current references, so we can set the delta i band is the current reference, ok. So, that is one of the advantage here, this is just the change in implementation strategy.

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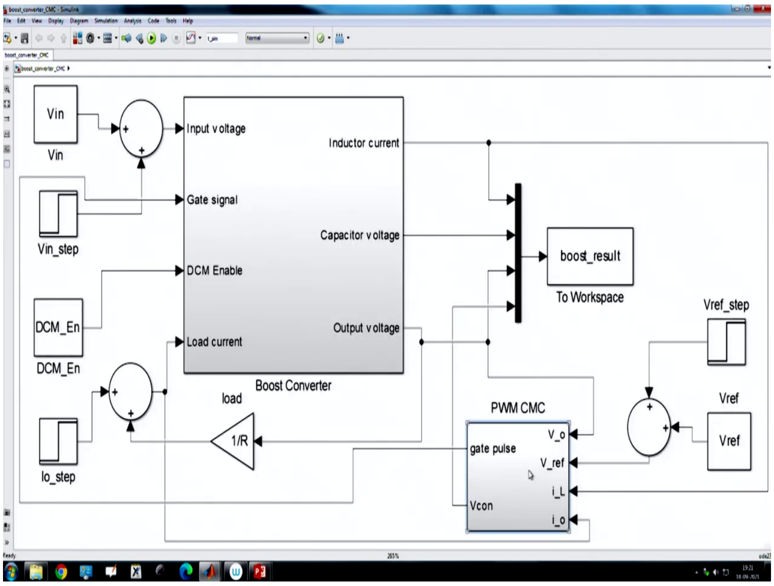

And for the other one, where the current mode control it is also well known already.

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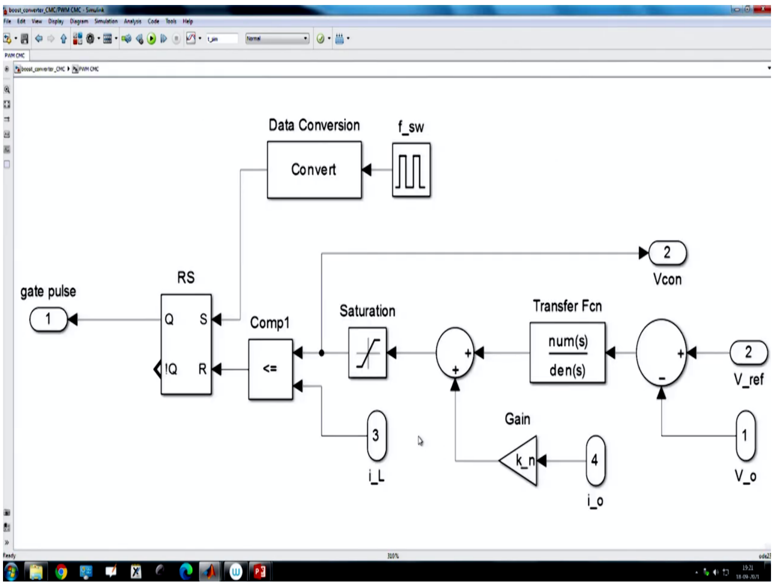

So, we have discussed multiple time where we have considered a load current feed forward because we want to you know increase the bandwidth, and we discuss that for large-signal tinning we can incorporate the load current feed forward.

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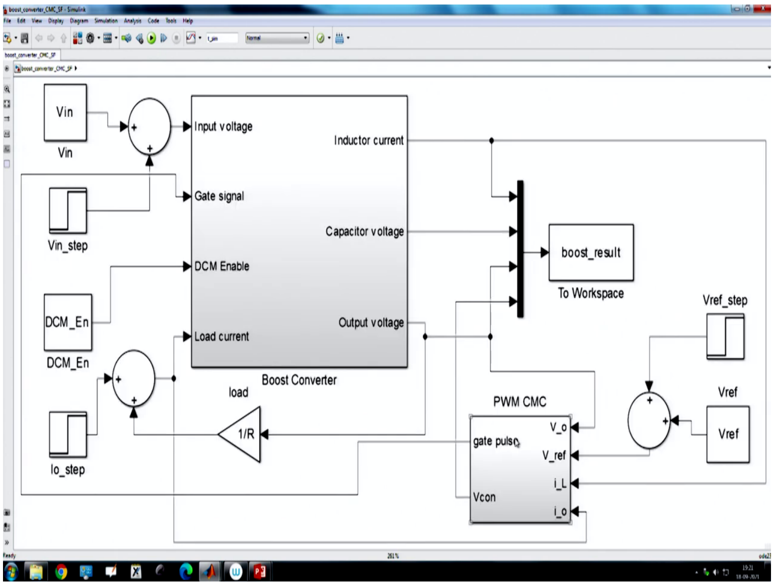

And in state feedback control, if we go, in state feedback control, we are taking the inductor current state, output voltage state.

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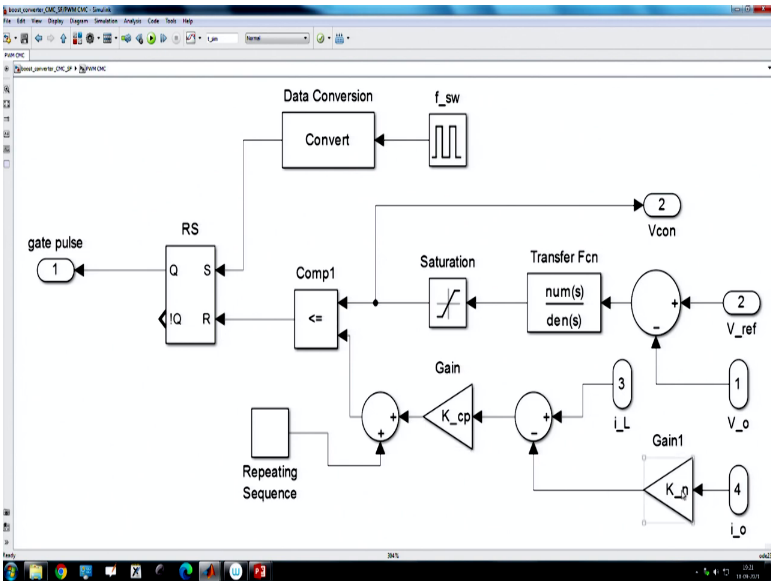

And also load information because if you go, we have a normalized load current state feed forward and inductor current, then the error current is multiplied with the state feedback gain and this transfer function we are using a PI controller where we assume designing the controller based on that our pole placement criteria. Because we are using an augmented state approach.

And this you know ramp will come when we run it because we have not run it, ok. So, let us go and do the simulation one by one.

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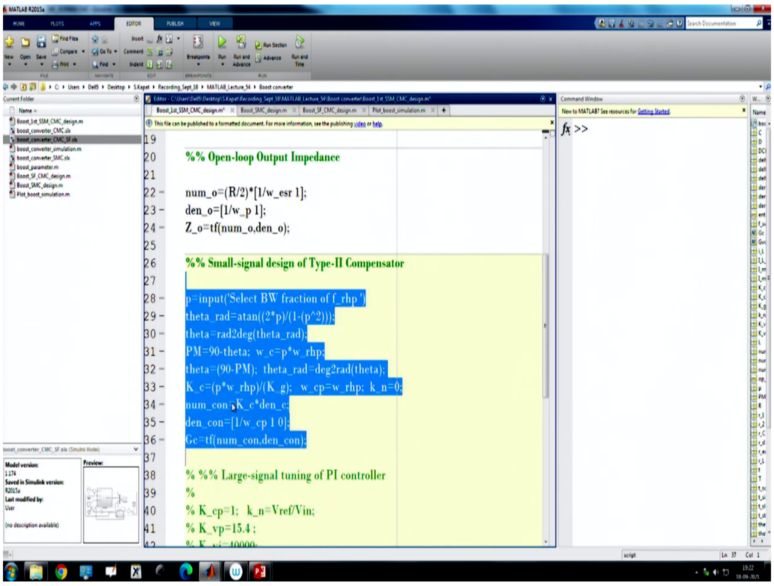

So, first we will run using regular current mode control, ok.

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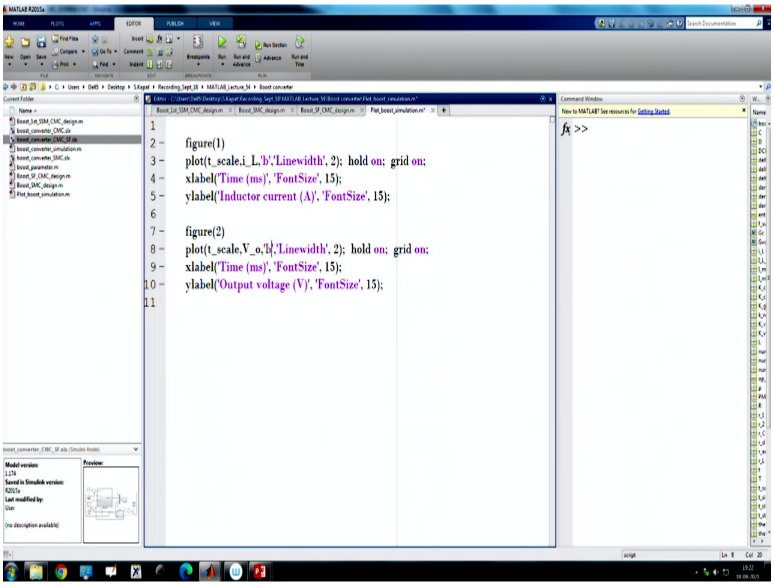

And we will use you know the first one regular current mode control, and we will see the reference transient performance.

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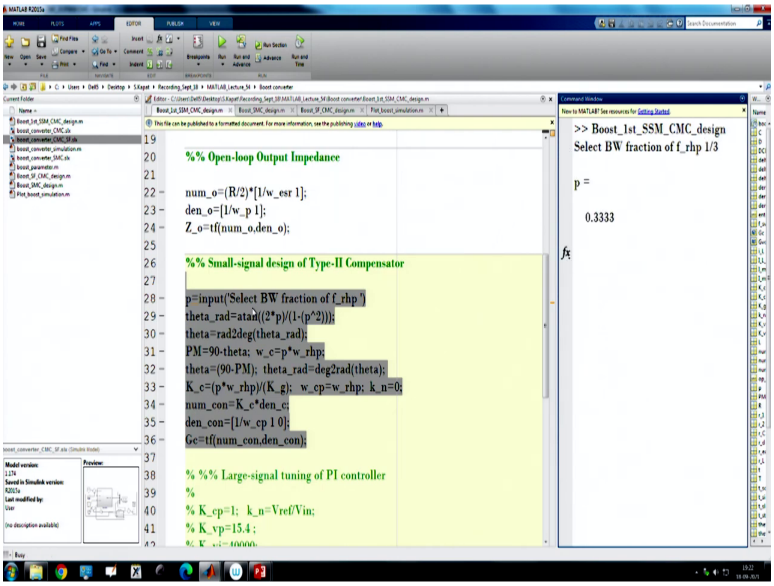

And we want to give one-third rhp 0 is the design.

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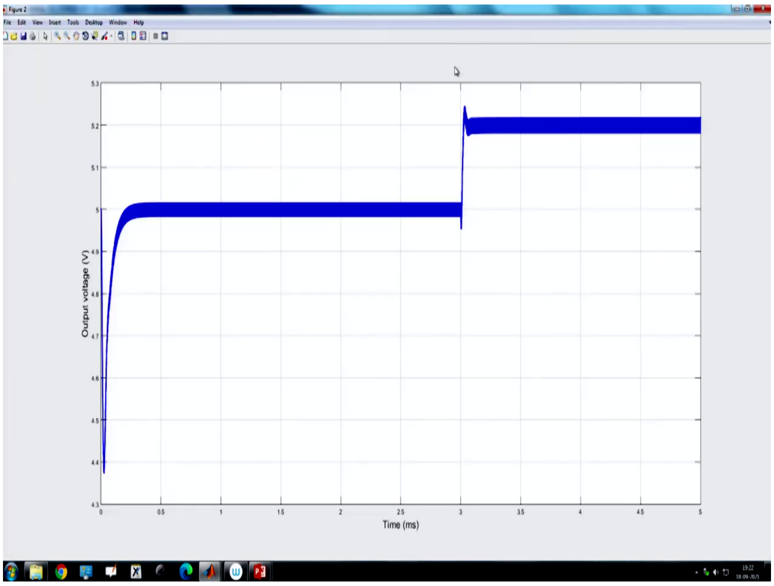

And this is the response that we are getting for one third of the rhp 0. So, it even has overshoot, undershoot, right, so one-third rhp 0.

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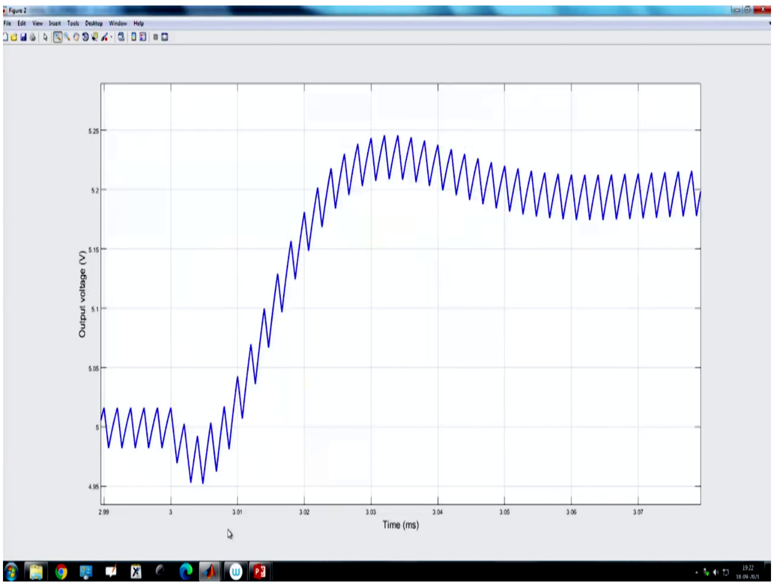

Now, we want to use our large-signal tuning, ok.

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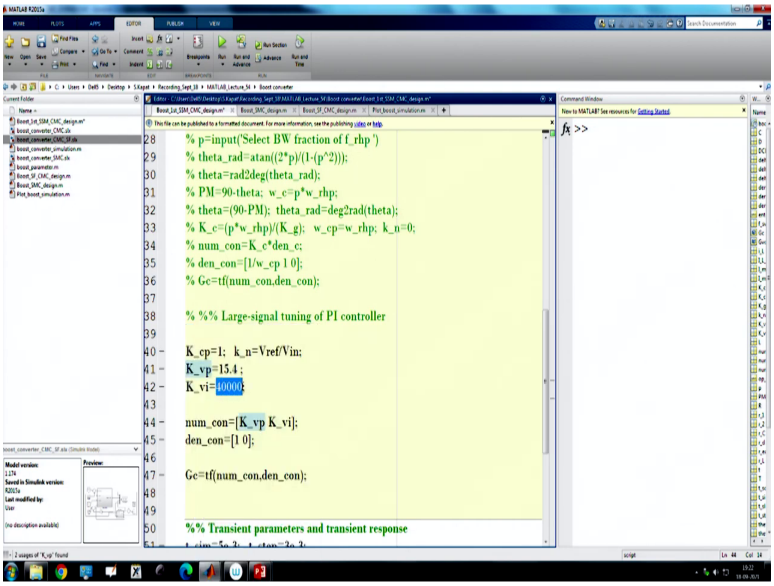

And this gain, we have obtained, so here we have also included our integral action, right? And we have obtained the gain by computation using our tuning rule and we want to use a different color.

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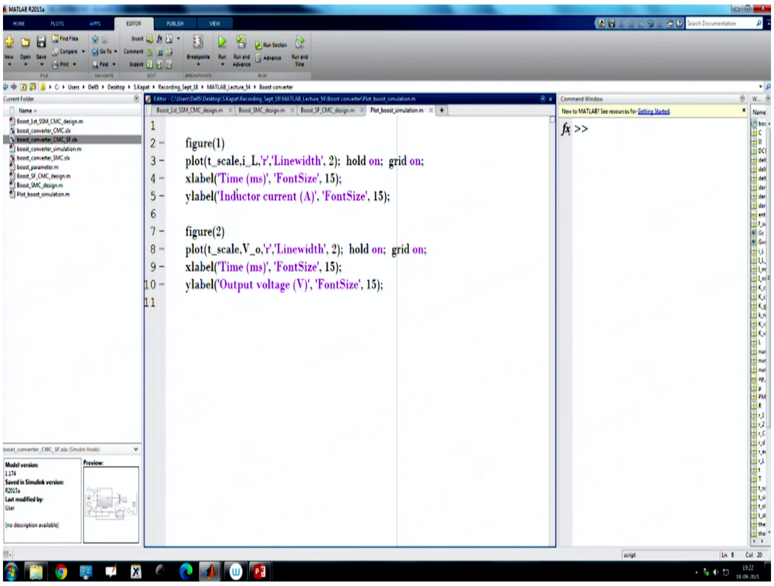

So, let us say we are using a red color trace and we are running it.

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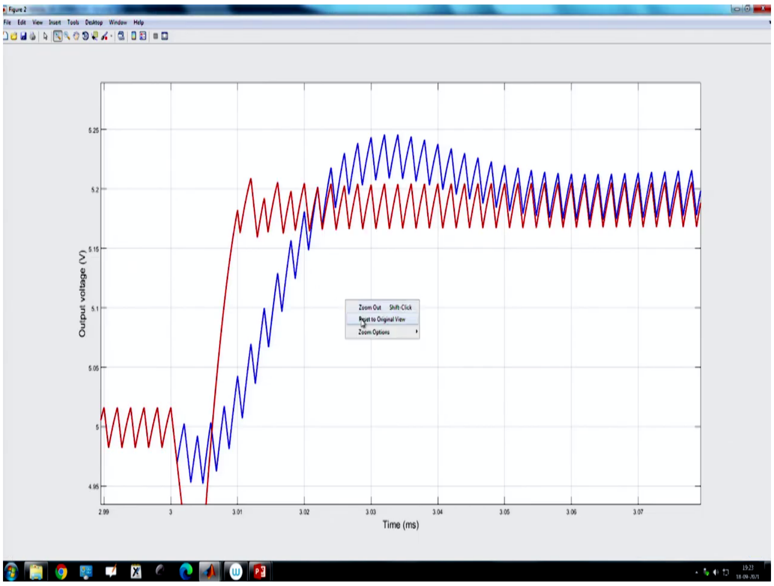

You will find the response is coming in one switching action, ok. So, it is like a time optimal, but there is a large undershoot and that we have discussed that in case of boost converter, since it is a non-minimum phase converter.

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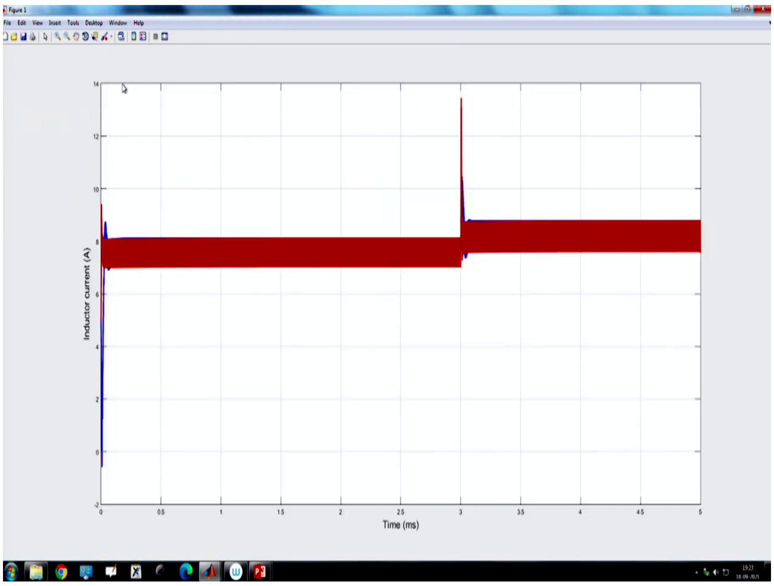

And if you go to the current waveform, since the inductor current using the optimal tuning is going, is turning on, the inductor current is going and going and it is 2-3 cycle it is continuously on, when the voltage is actually discharging. So, as a result, you will get more undershoot.

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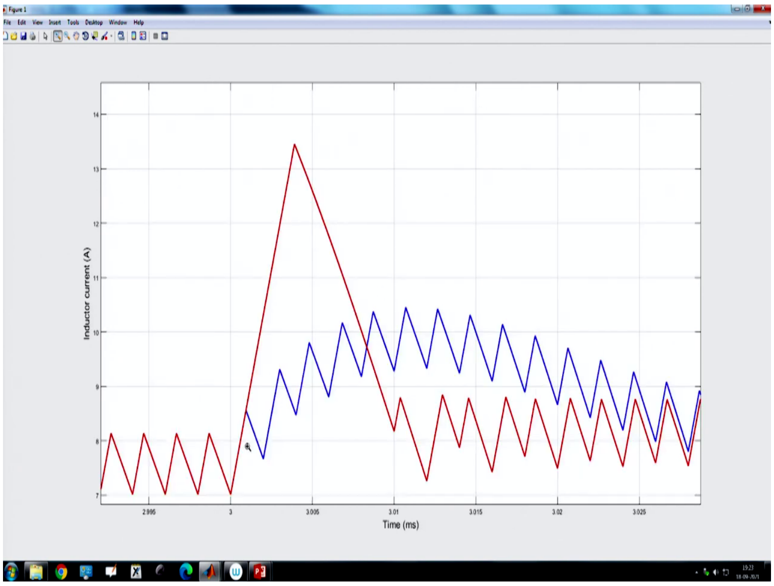

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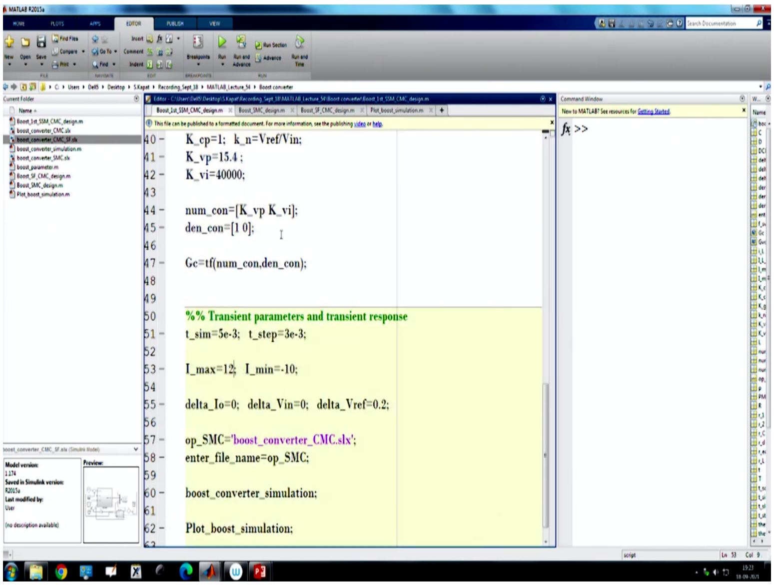

But if we put a current limit for the same result, suppose, if we put a current limit of 12 ampere, then you know we want to just use another color red you know instead of green, we can use green color.

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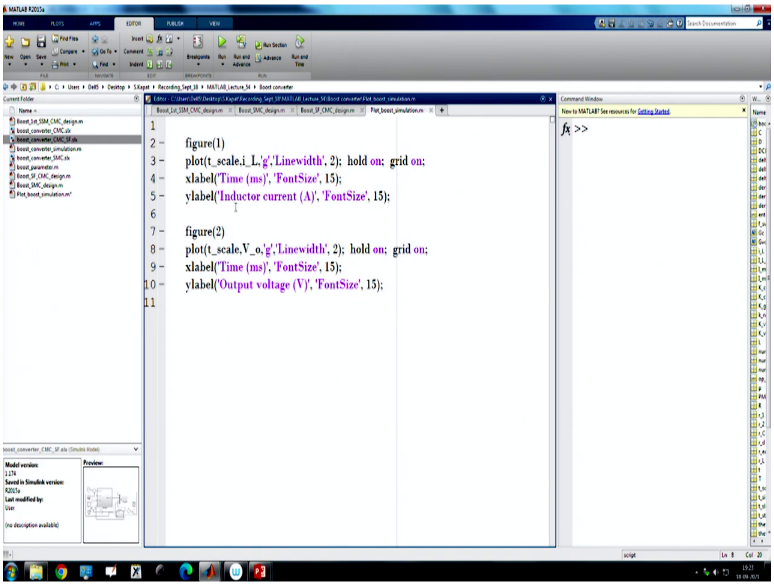

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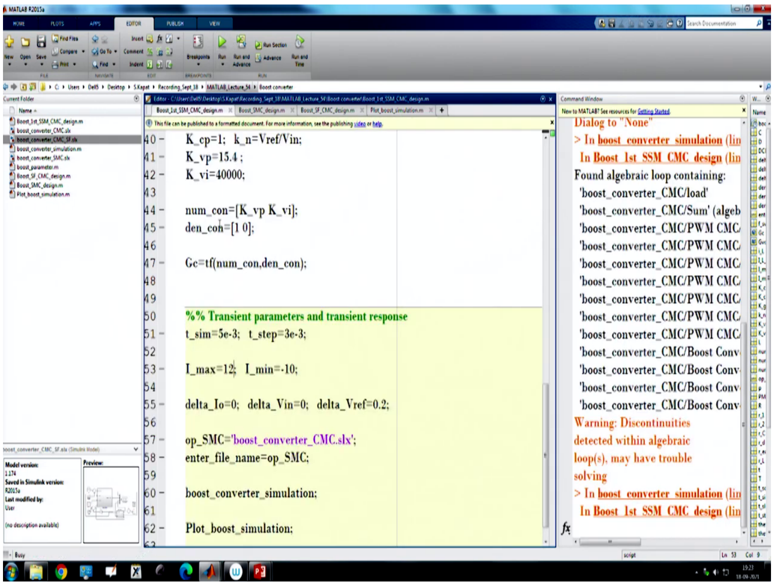

Then, if we rerun it, now, we are putting a current limit of 12 ampere, ok.

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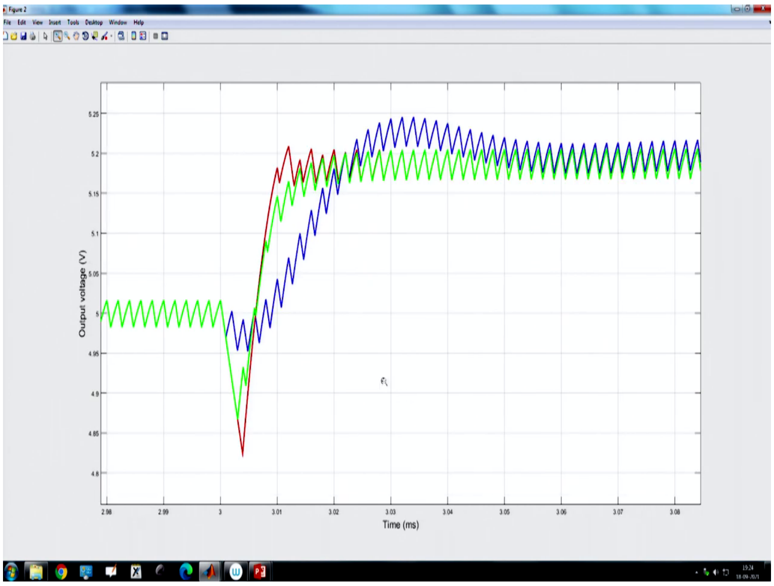

And if you go and check that we have set a current limit, we have reduced the current, but the response is still much faster than our linear control, ok. So, it is much faster than our linear control.

Now, we will go for sliding mode control, ok.

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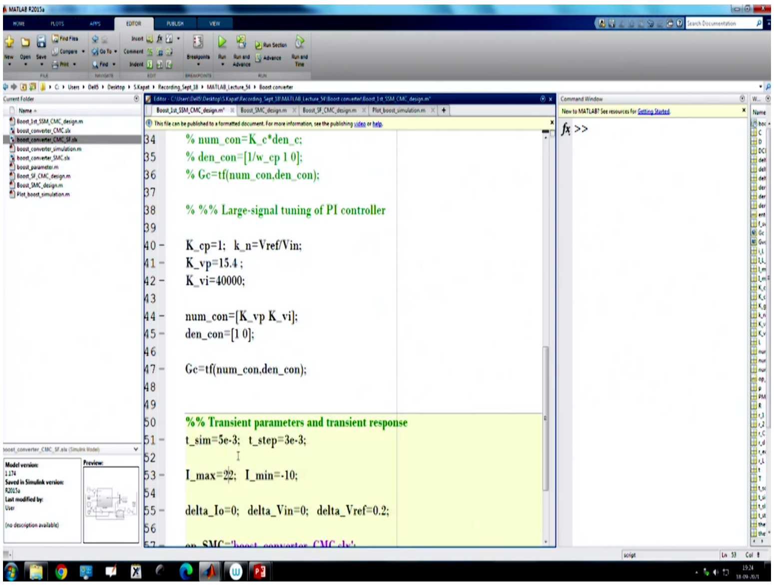

So, here we will remove all, ok. And we want to consider the optimal criteria. There is no as such current limit.

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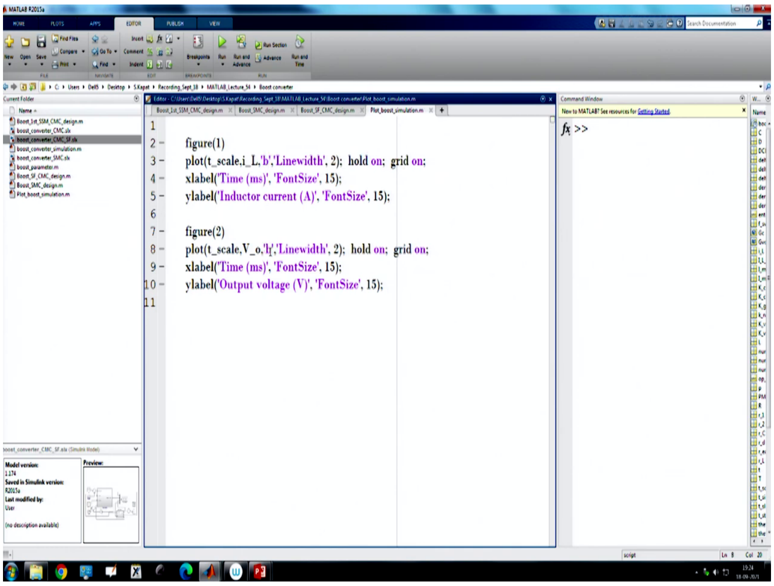

And we will consider our one large-signal tuning using blue color.

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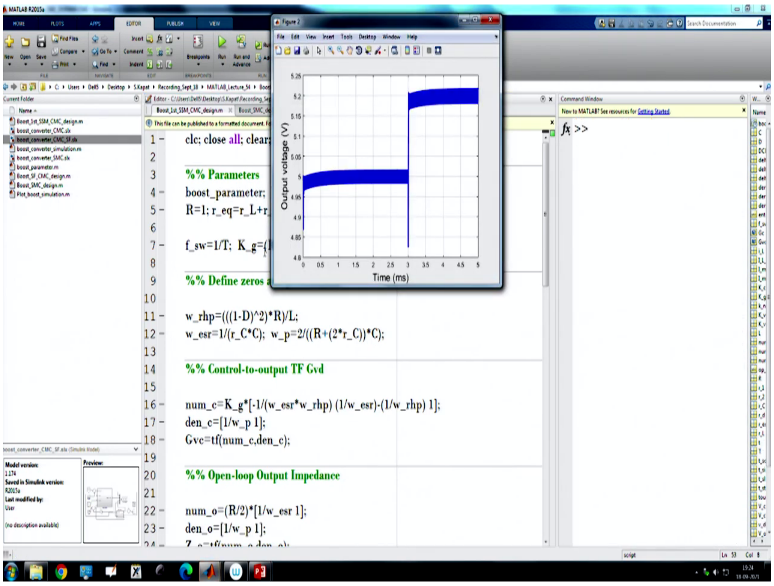

Now, let us go. So, large-signal tuning this is our blue color. Now, we are going for sliding mode control. So, sliding mode control, we have designed, sorry sliding mode control just to get a kind of optimal criteria, optimal you know gain criteria.

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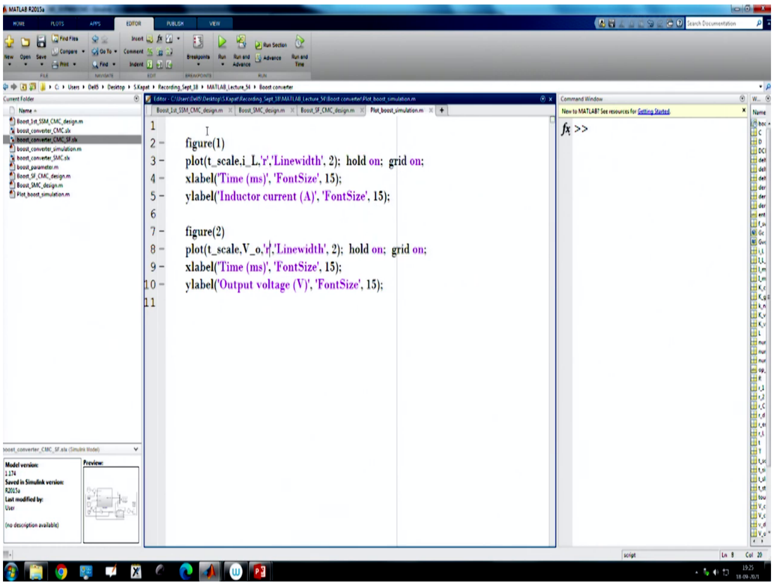

And let us see, if we run it, and we are using red color for the sliding mode control.

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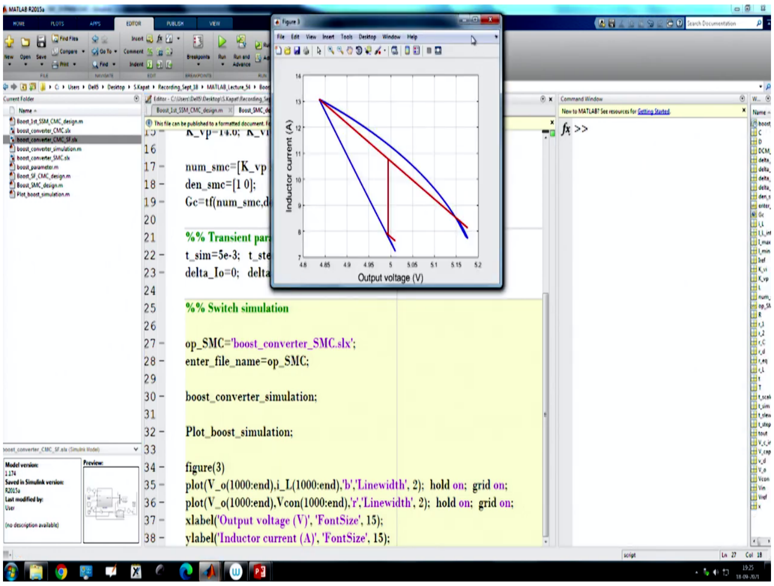

And if we design, if we run it, we want to see how does the response look like under sliding mode control.

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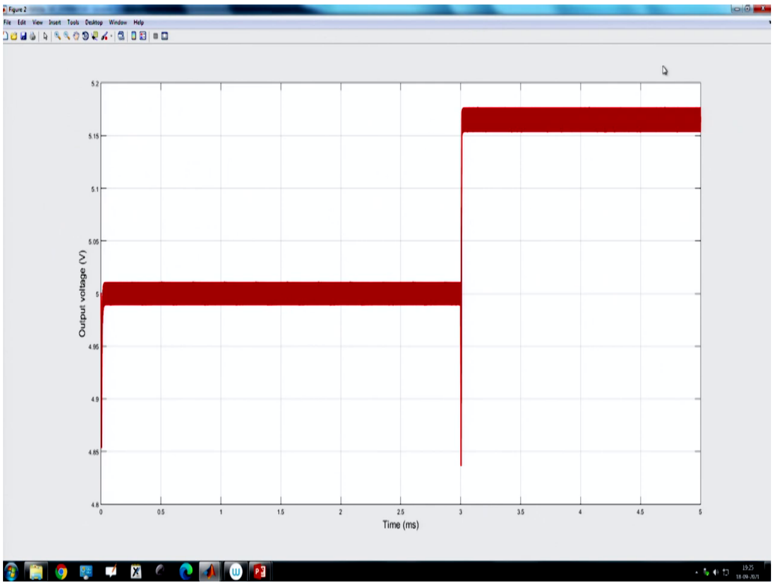

I think we have eliminated this, sorry.

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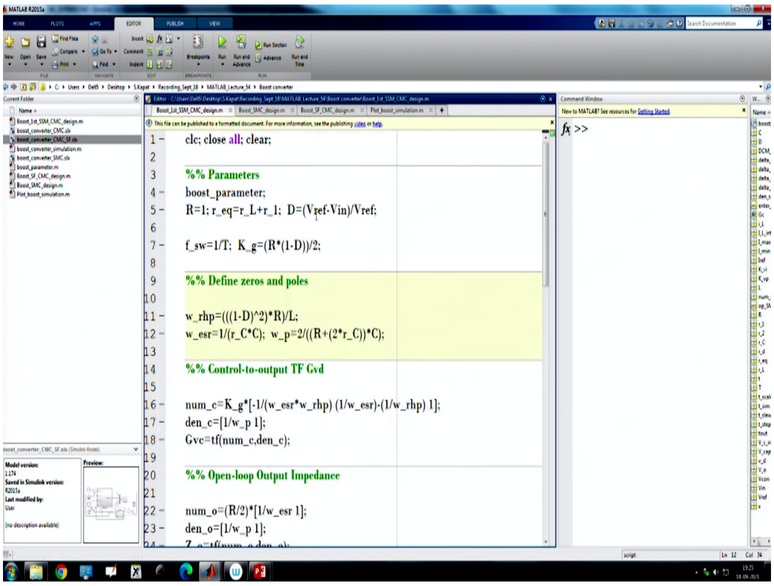

So, again, we have to run it.

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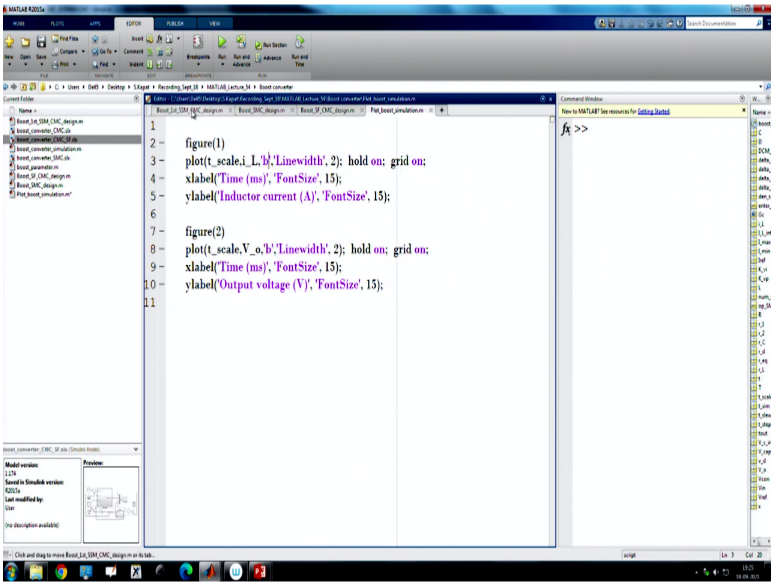

Our tuning will be blue because we have removed the overlap.

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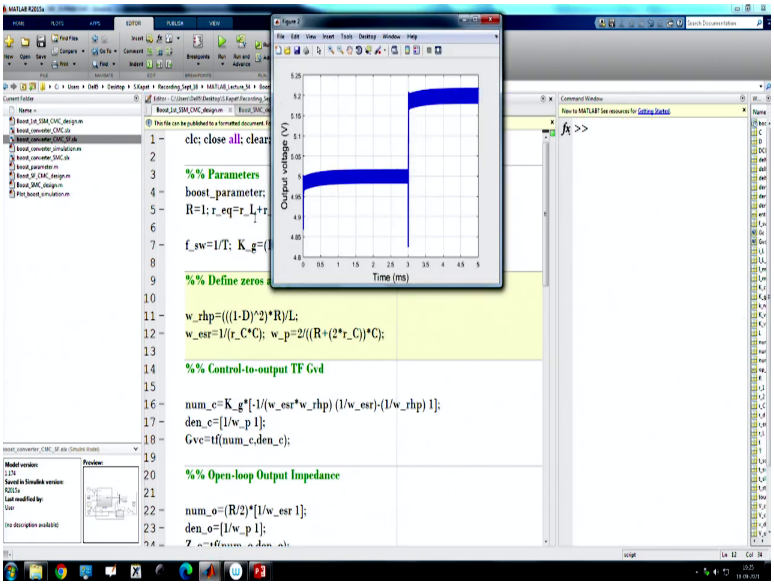

I mean, so overlap we have to clear the waveform, close the wave all the waveform. So, sliding mode control, we want to use red color.

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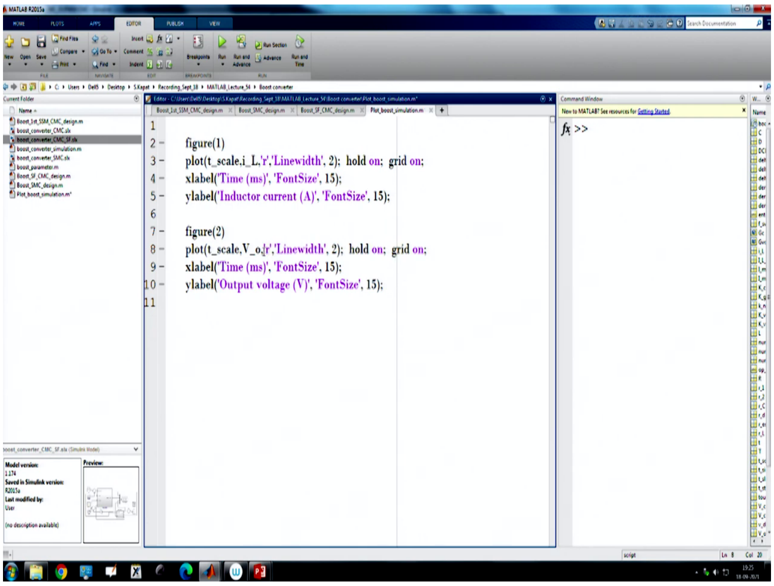

Red trace, and this now we want to compare.

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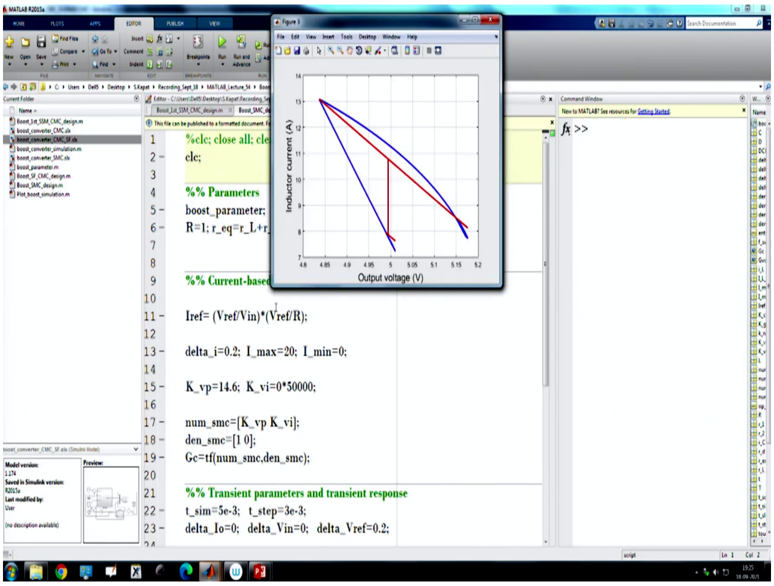

So, we want to compare the two responses, and you can see that sliding mode control the switching frequency is different because your hysteresis band has to be set according to in order to get the desired this reference.

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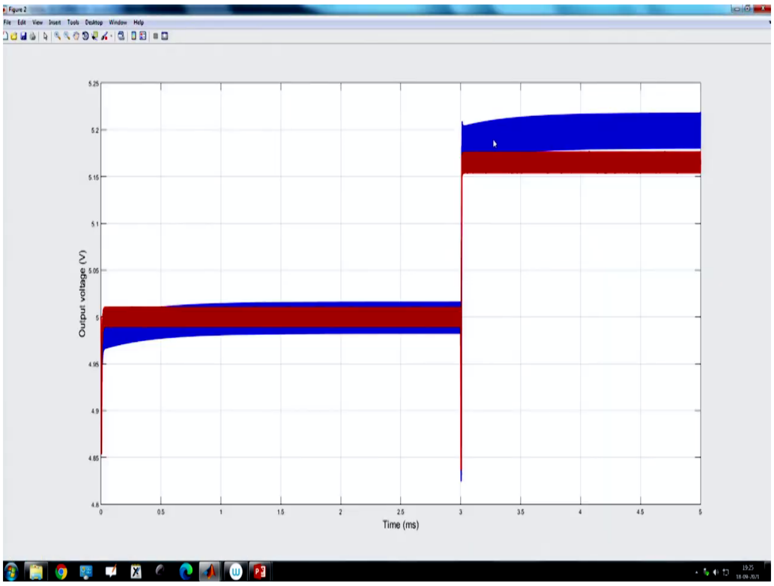

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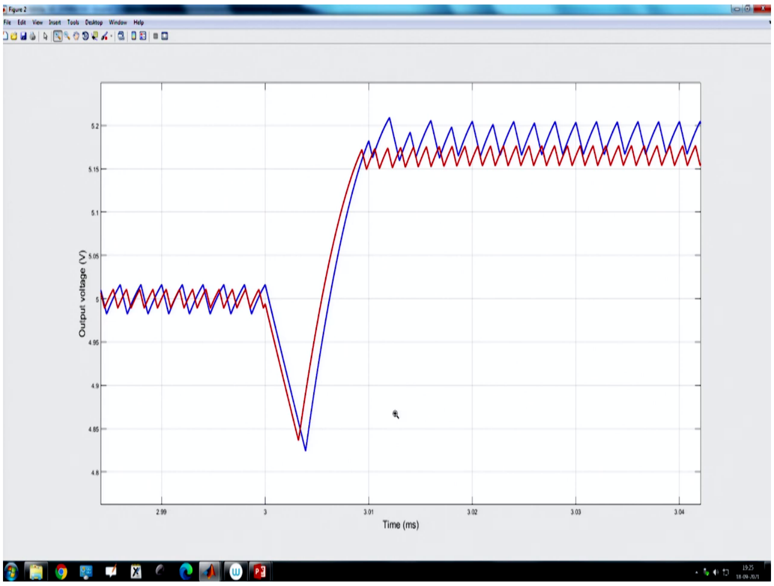

And also, there is a steady state error because we have not considered any integral action in the sliding mode control. As a result, the output voltage average is not set to a desired value. Whereas, the large-signal tuning we have an integral action, it is slowly going to your average value is going to 5.2. So, that means, the regulation is happening also the switching frequency is fixed.

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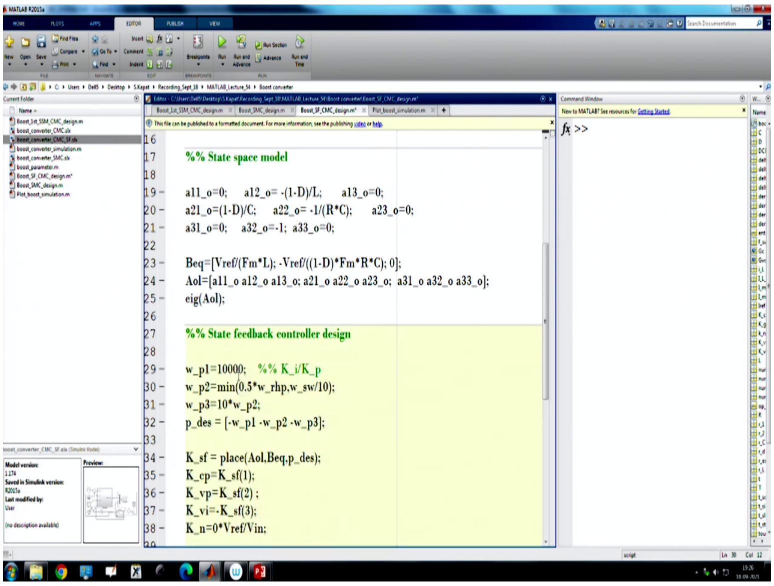

Next, we want to consider the large you know the state feedback control. So, here we want to again you know, first we want to design based on our small-signal criteria where we want to use 0.5 rhp.

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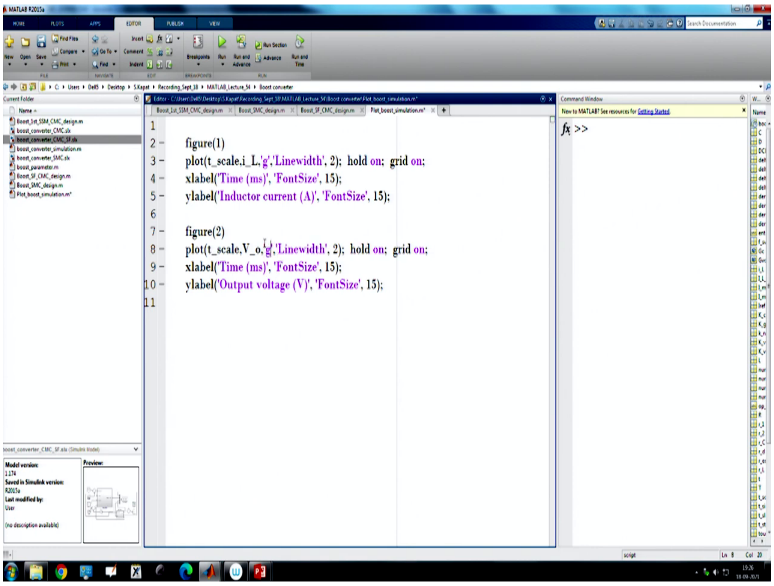

And now we are using green color. This is our state feedback design. So, I mean we should get a better response than linear control, but let us see how does it looks like, ok. So, stake feedback control, and we have used green color.

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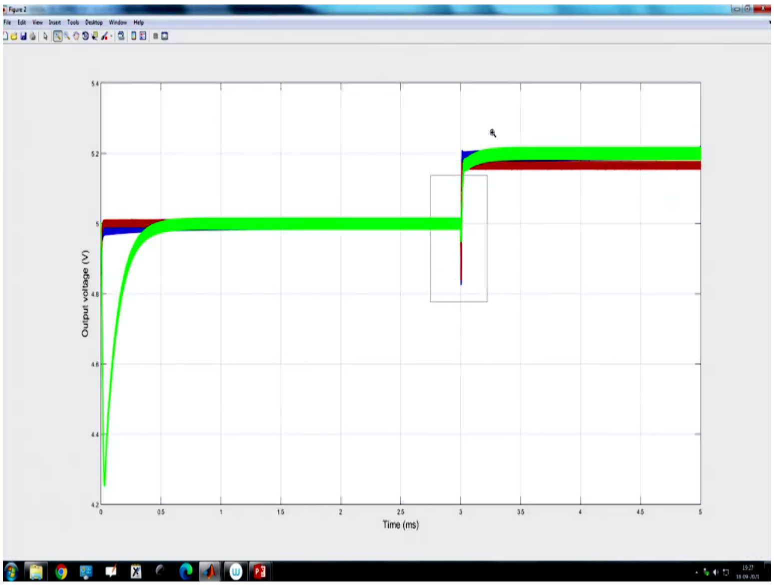

Naturally, this is the linear design using linear feedback. So, it will be sluggish because it is up to half of the rhp 0.

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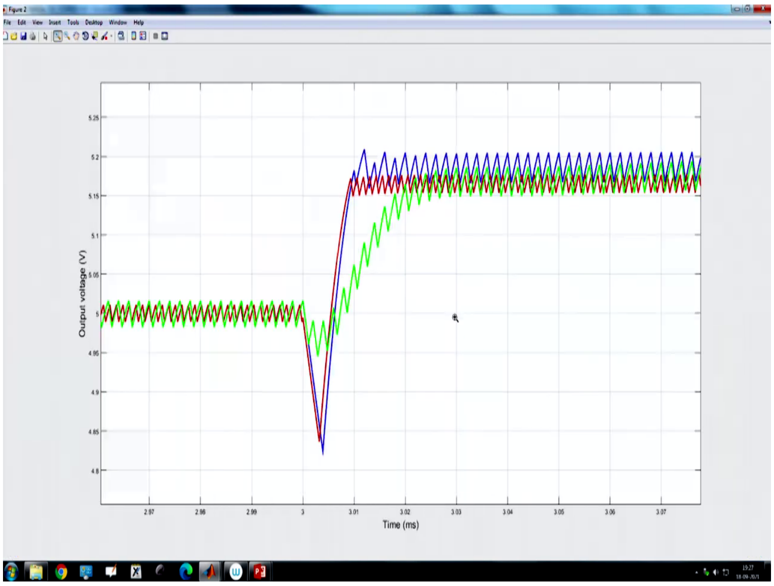

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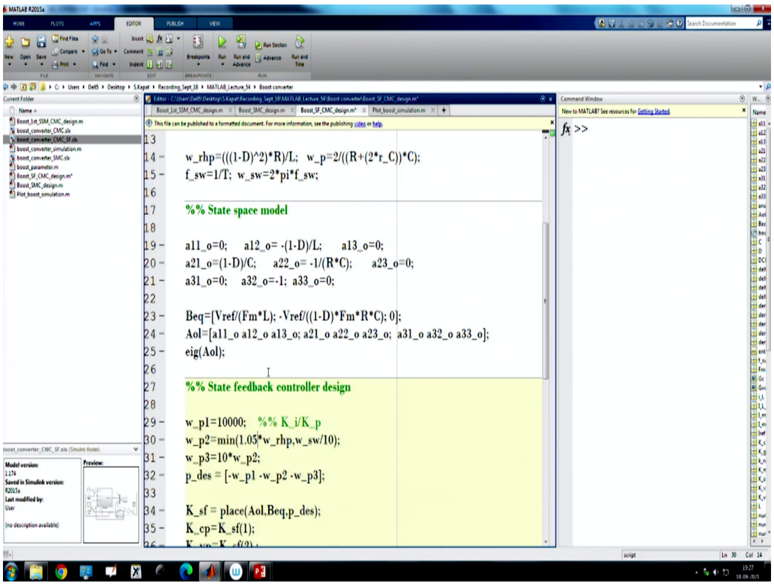

Now, since, we have discussed large-signal stability, so if we go up to 1.05; that means we are going crossover frequency beyond rhp 0 and our small-signal model shows it is not simply possible. But using large-signal Lyapunov stability, can you really achieve it or not? So, we are designing again using state feedback control to achieve a crossover frequency 1.05 times of the rhp 0, that means it is higher. And we are using a black color.

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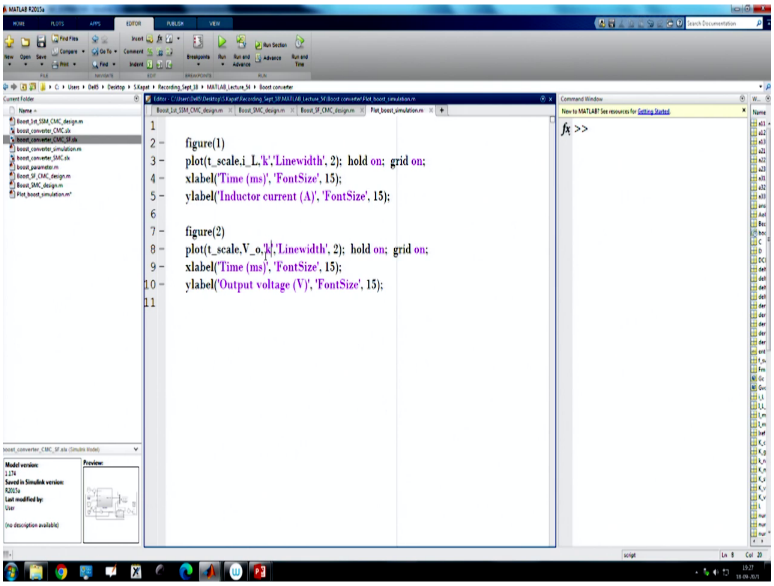

So, linear model is not at all valid and as per linear model it is unstable. But we want to see what happens in this case. So, let us see. So, the black color is the one.

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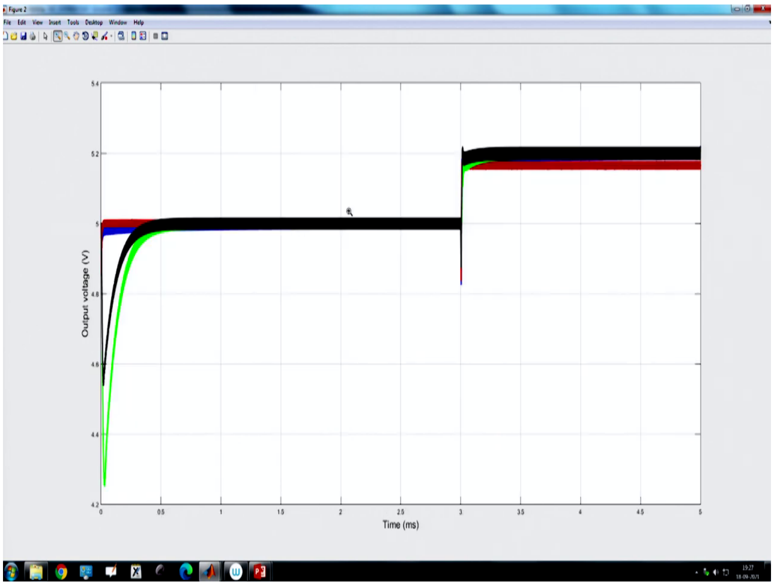

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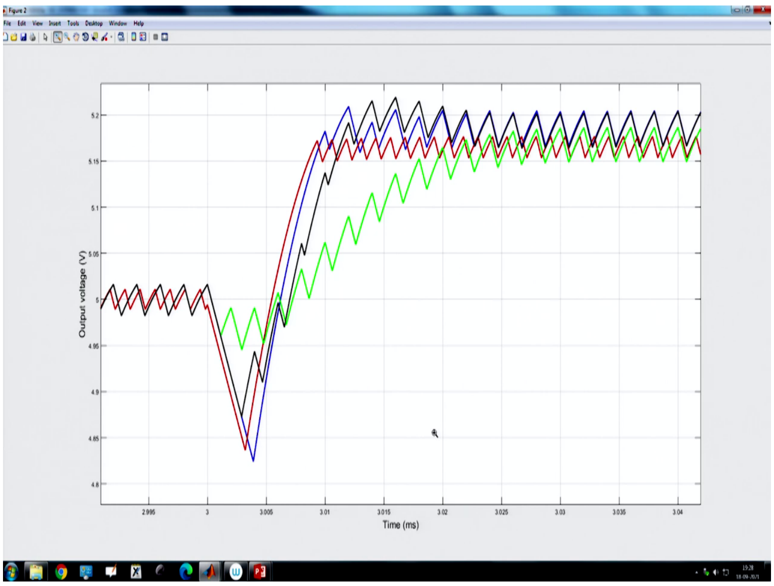

So, you will see it is not unstable, that means, you are getting even fast response. It is not time optimal, but it is also somewhat close to time optimal because there are multiple switchings.

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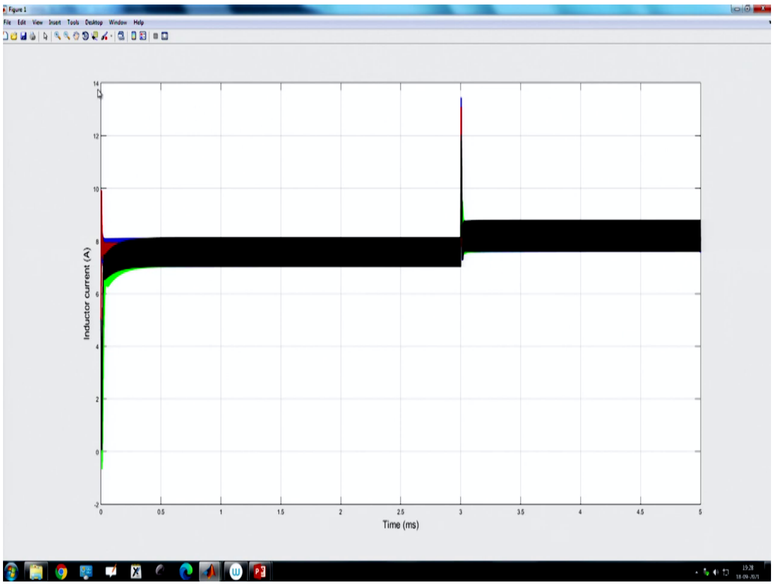

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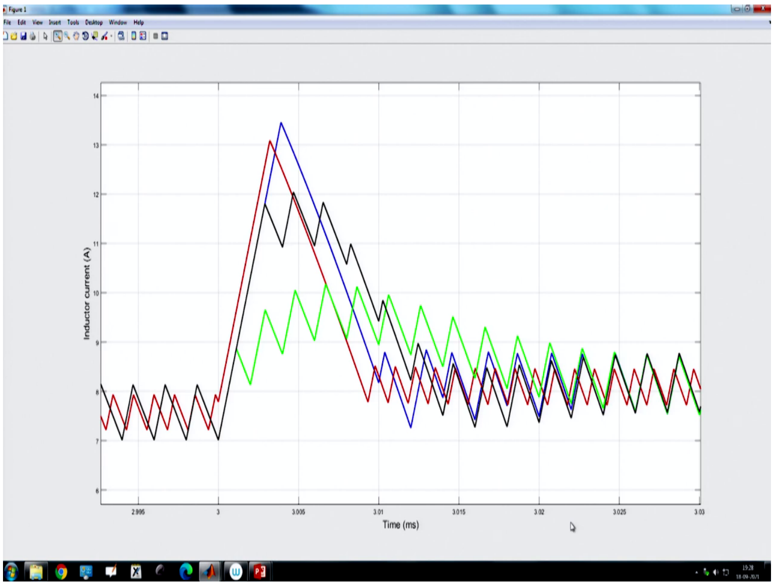

And if you compare the current waveform, that means the response is happening perfectly fine. You know this is a black color. And, but linear model is invalid, and also as per the linear model, we have shown even whether it is a current mode or voltage mode from loop transfer function equation and the at crossover frequency, you cannot achieve crossover frequency above rhp 0 because that are showing unstable. But that is where the limitation of the linear controller.

But when you go for Lyapunov based stability, and we have ensured the large-signal stability is retain then even we can push to go beyond that. But in this case, the linear model and the bandwidth concept are not valid. But in some sense of bandwidth we can push the performance even much higher than what is possible to achieve using linear model, ok.

So, we have discussed this comparative study large-signal tuning of a boost converter, and that means, we can go even further in case the performance as long as we satisfy our Lyapunov stability criteria that we have discussed in the here. So, we can satisfy that v dot is negative. And that we have checked, and for high gain even it is stable.

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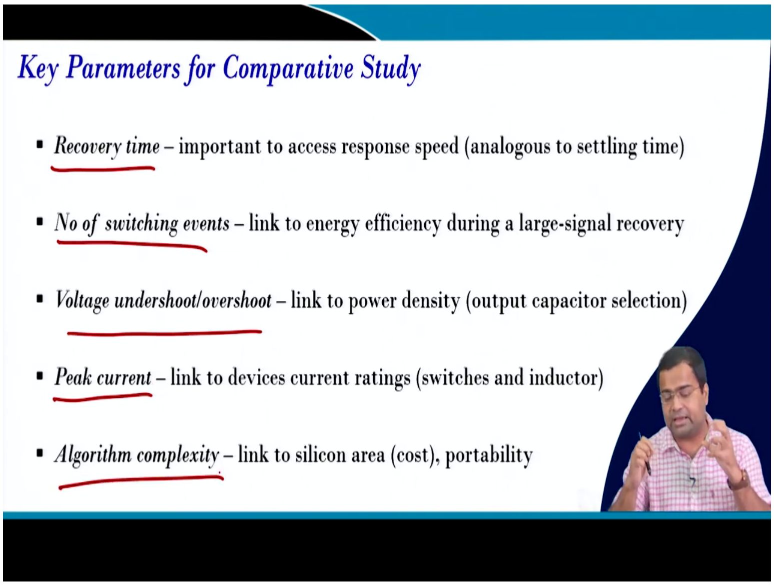

So, the key comparative performance, which are very important in order to compare is the recovery time that is important. We need to make it fast, and we will see that it will also increase the energy efficiency.

Number of switching event should be reduced to have higher energy efficiency. Voltage undershoot also needs to be reduced, and you saw that if you want to really speed up sometime the undershoot was large, so that can be managed by putting a current limit, and in some cases, we can use the combine current and voltage linear, particularly for a boost converter. But for a buck converter, minimum undershoot can be achieved even using time optimal control, but for boost converter undershoot was more we need to put a limit.

Peak current was the concern, but in our large-signal tuning we can always put a current limit because it is using current mode control and then your performance will be much better than linear control.

And the algorithm complexity, so the large-signal tuning it uses our existing current mode and voltage mode control algorithm, whereas you know if you go for sliding mode control, if you go for second order switching surface boundary control, those are require some nonlinear function and also they are variable frequency operation. But here, large-signal tuning can be applied for fixed frequency, both for buck converter and boost converter.

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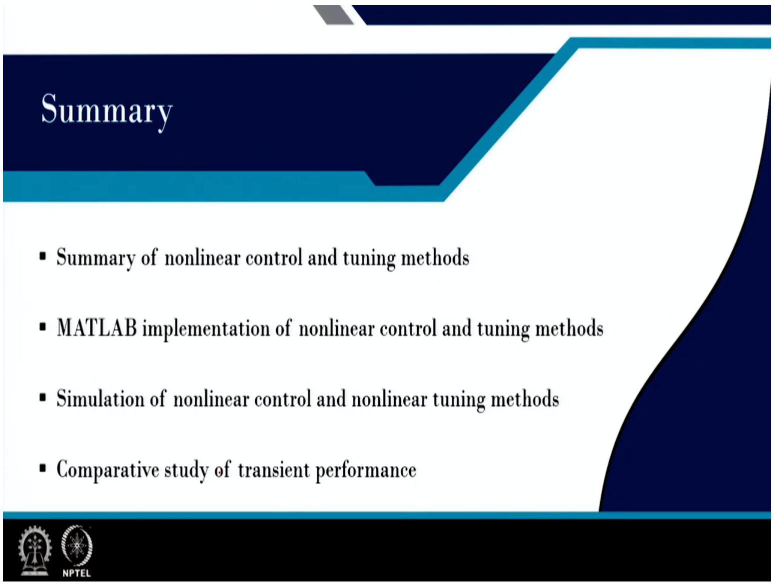

So, with this, I want to summarize we have discussed multiple nonlinear control and tuning method, MATLAB implementation of nonlinear control and tuning method, simulation case study we have demonstrated. And we have assessed some comparative case study for different using different control and tuning algorithm for buck and boost converter.

And we want to summarize the performance improvement as well as the possibility of size reduction using this large-signal based control. It includes both large-signal based nonlinear control as well as the large-signal based tuning. So, that is going to the future trend to improve performance efficiency as well as you know in order to reduce the size. That we are going to discuss in the next class. So, with this I want to finish it here.

Thank you very much.