Control and Tuning Methods in Switched Mode Power Converters
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Module - 12
Performance Comparison and Simulation
Lecture - 55
Small-Signal vs. Large-signal Tuning: Comparision Using MATLAB Simulation

Welcome, this is lecture number 55. In this lecture we are going to talk about Small-signal and Large-signal based Tuning and their Comparison Using MATLAB Simulation.

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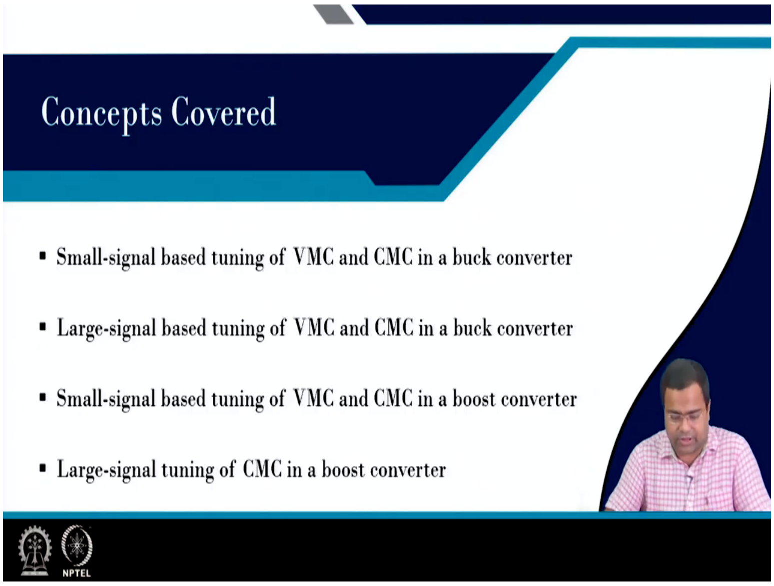

So, here we will first talk about small-signal based design and tuning of voltage mode and current mode control in a buck converter. Then we will talk about large-signal based tuning of voltage mode current mode control; that means, both are in buck converter. Then we will talk about small-signal based tuning of voltage mode and current mode control in a boost converter and then, finally, large-signal tuning in a current mode control boost converter.

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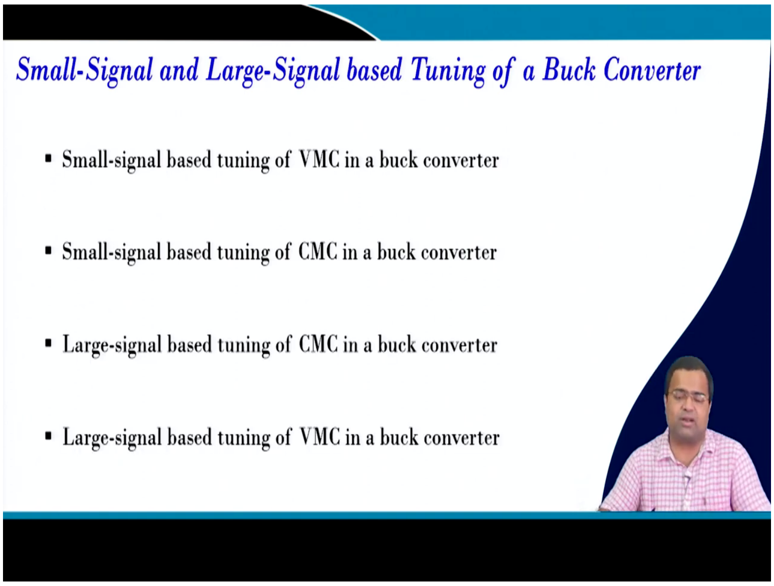

So, if we recall I am not going to again because we have already discussed the tuning methodology small-signal as well as large-signal in sufficient detail. So, first in the buck converter we will take a voltage mode control, current mode control both are designed using small-signal model. Then, in a large-signal model, we have designed both current mode and voltage mode control.

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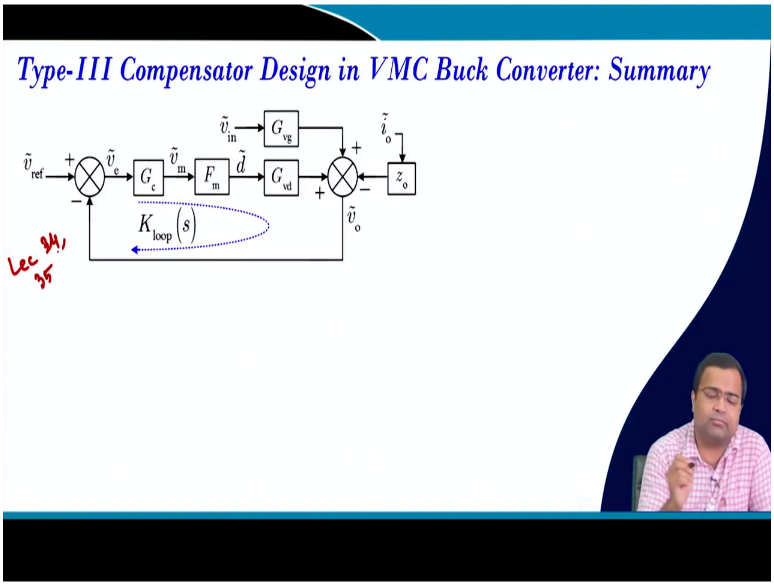

So, if you recall our voltage mode control design you know. So, we this is the loop transfer function that we have discussed multiple time you know you will get more detail in lecture number if you go to lecture number 34, 35 both have like an extensive design.

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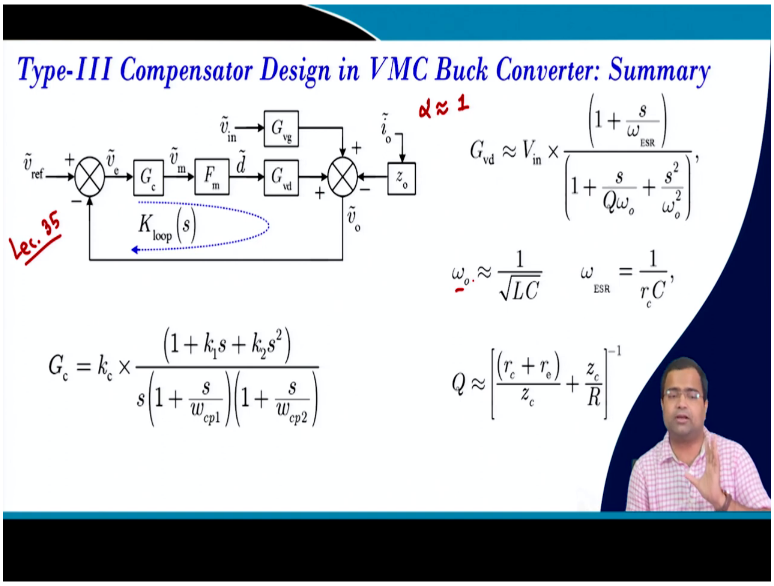

For type 3 compensator I think you have to go to lecture number lecture 35. So, details are available. So, where the G vd is given and if you are considering you know alpha term, if you are considering alpha to be almost equal to 1, then it simplified to ESR zero. And if we take omega 0 to be 1 by square root of LC because the r plus rc by r plus rl re both are more or less same. So, we have approximated and that we have discussed and Q factor as well.

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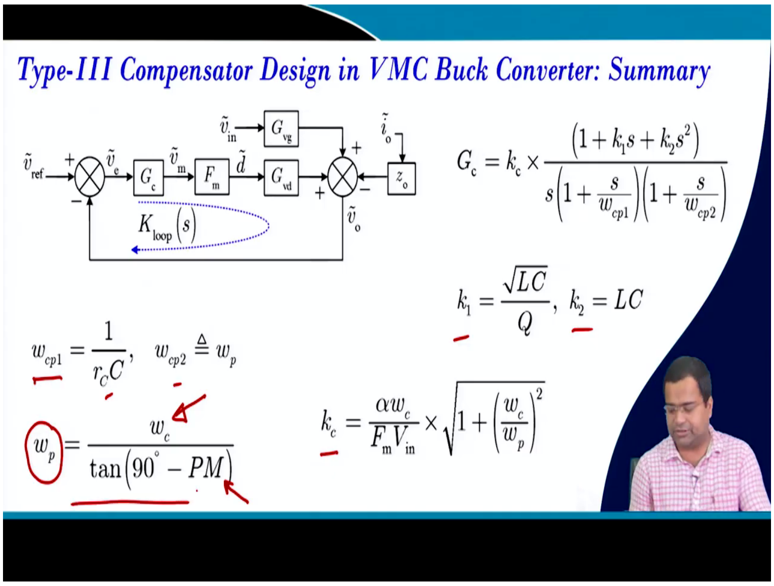

So, this is a transfer function and we need a type 3 compensator that we have discussed. And then how to change you know for exact you know perfect compensation by analytical pole zero compensation. We know we can cancel one controller pole to cancel ESR zero one controller another controller pole is flexible.

And the controller zeros are placed to cancel the control to output transformation pole ok. And then you know we know that how to obtain this omega p which is nothing but our flexible controller pole and that required two information. We need to provide what is my crossover frequency.

And generally we take up to one tenth of the switching frequency and then we need to specify the phase margin and we have discussed detail model matching and all. And we know the controller gain will turn out to be the ratio of omega c by omega p; where omega c is the crossover frequency and omega p is the pole frequency that we will obtain from this equation.

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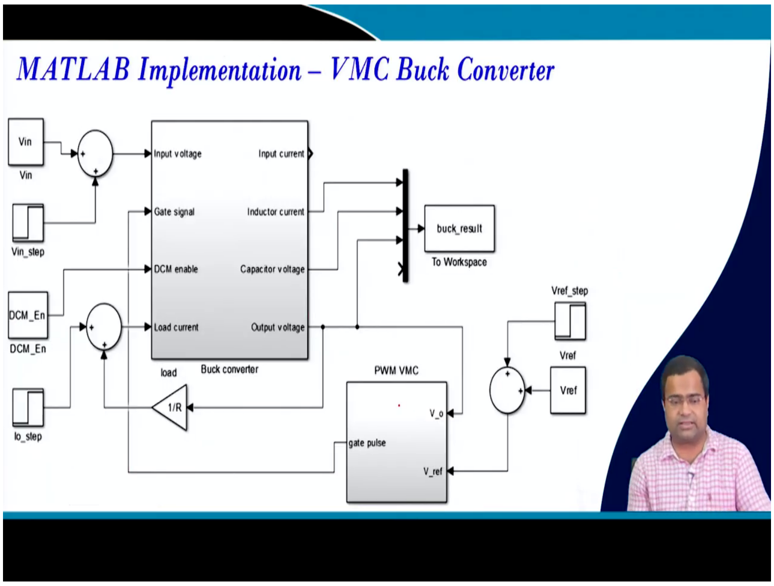

And we I we have already discussed multiple time the block diagram MATLAB diagram of the voltage mode control, which we are not going to discuss again right.

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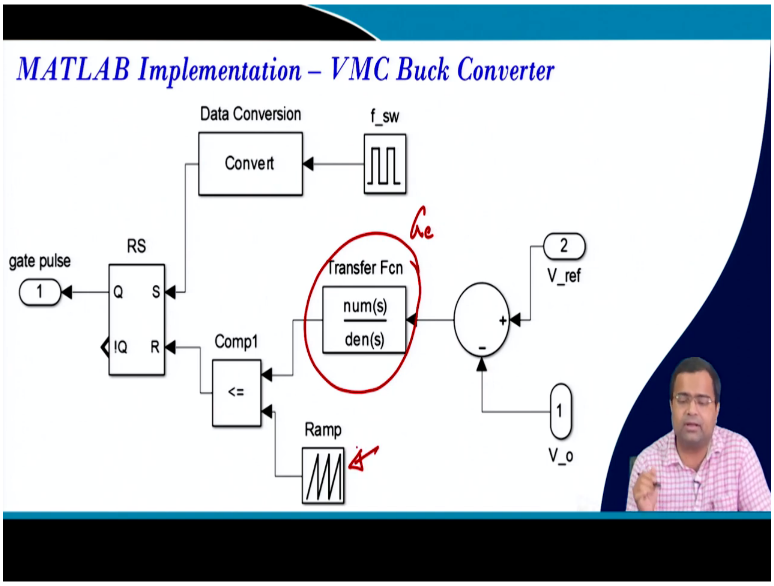

And again, in this voltage mode control, we have we are setting the compensator. This is our Gc controller type 3 compensator that we are setting from our MATLAB code. And we know how to design if we it will ask for phase merge sorry it will ask for phase margin as well as gain crossover frequency and then buck converter you will have a two flexible in a choice right and you need to provide the ramp in order to find out the controller gain.

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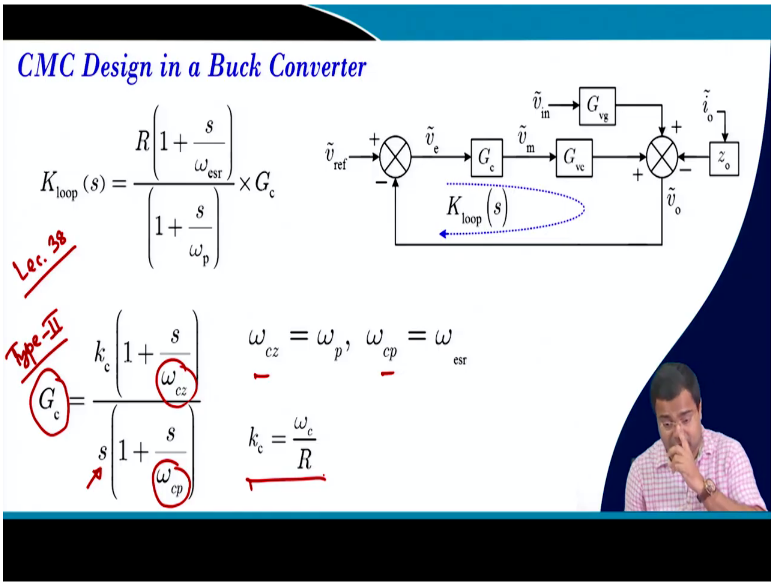

Then, for the current mode controller design in a buck converter, if we recapitulate our loop transfer function takes like a first order system, then we need to take the controller, which is a type 2 compensator. It is like a type 2 compensator that we have discussed in I think it is lecture number 38 we discussed in sufficient detail.

So, you will find lecture 38 ok where omega cz, omega p, omega cp, omega esr all are discussed how to place the controller zero and controller pole; because we have one controller zero, one controller pole that we have to cancel and another pole is at origin. So, you will get a first order system right and how to get kc the controller gain that we also discussed.

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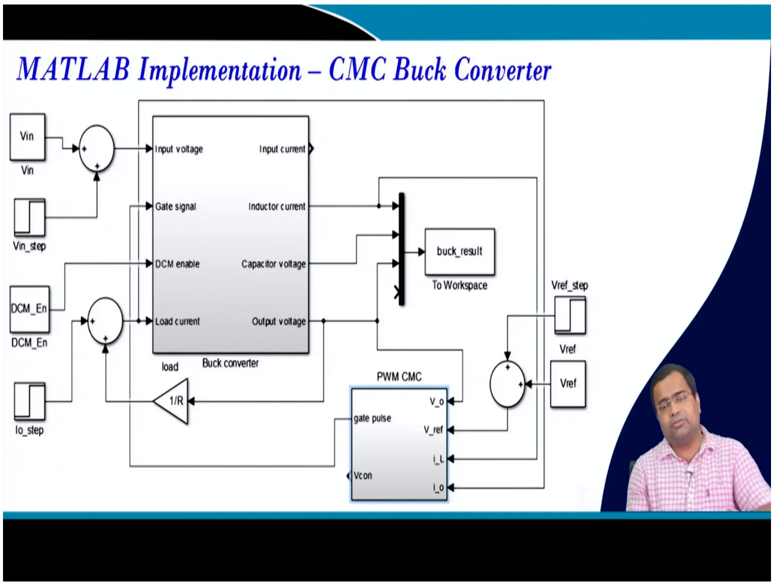

And we have also discussed the MATLAB model under current mode control. This has been you know we have discussed multiple time how to implement current mode control buck converter.

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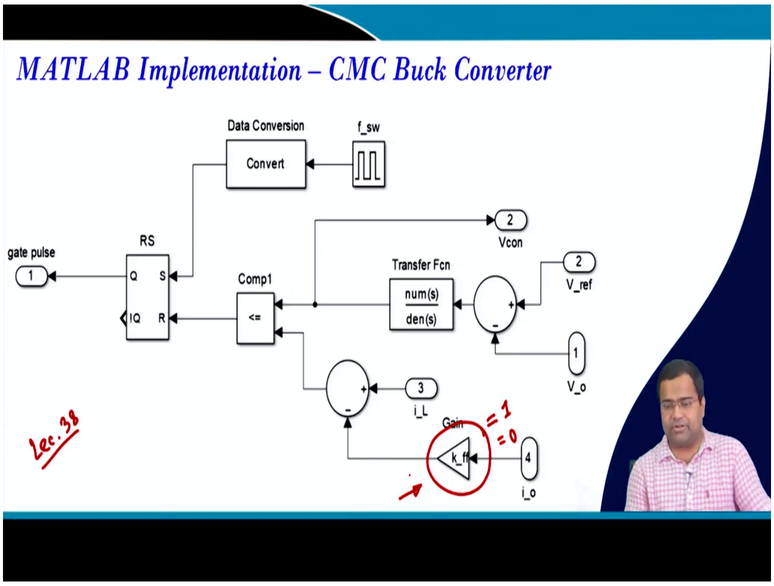

And you know here we are also considering an additional load current feedforward, either you can put it 1, then it will be a load current feedback and if you set to 0 then there is no load current feedforward ok. So, you know in regular current mode control we have discussed in lecture 38 what we have discussed that if you do not consider load feedforward then the current mode control performance is sluggish.

But, if you consider load current feedforward then you can make the output impedance close to 0, but there will be some finite slew rate due to the characteristic impedance. But, if you talk about reference transient because you are talking about the bandwidth then you will find during the reference transient there will be hardly you know this gain even if you do not consider it does not matter ok. So, in a buck converter we are going to consider load transient performance ok.

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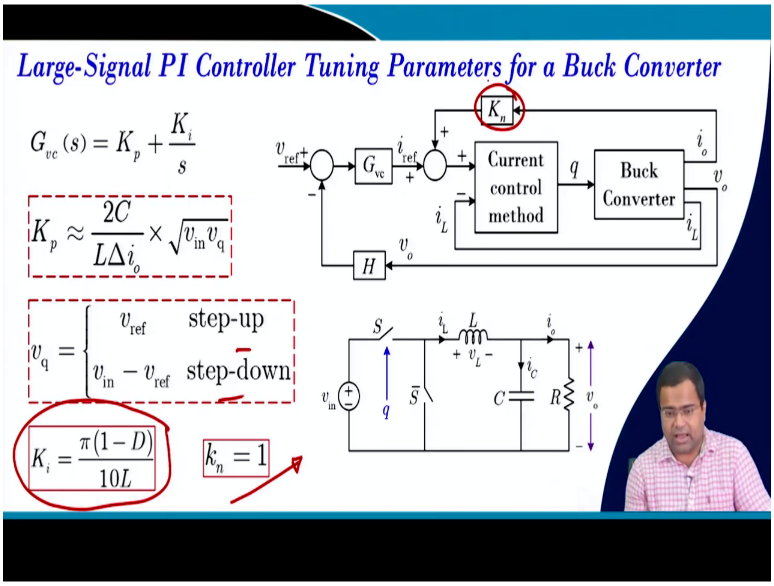

And then we also discussed in lecture number I think lecture number 50 the PI controller tuning parameter of a buck converter where K p we discussed where we have two separate gains for step up and step down that we have discussed. And then we have said we have also discussed that how to design this integral gain by means of small-signal model that also we have discussed in sufficient detail.

And for load current feedforward we need to consider normally load current gain to be 1 for buck converter right. And we have also discussed and how to implement it is a standard current mode control that is just now we have discussed and we are considering the load current feedforward.

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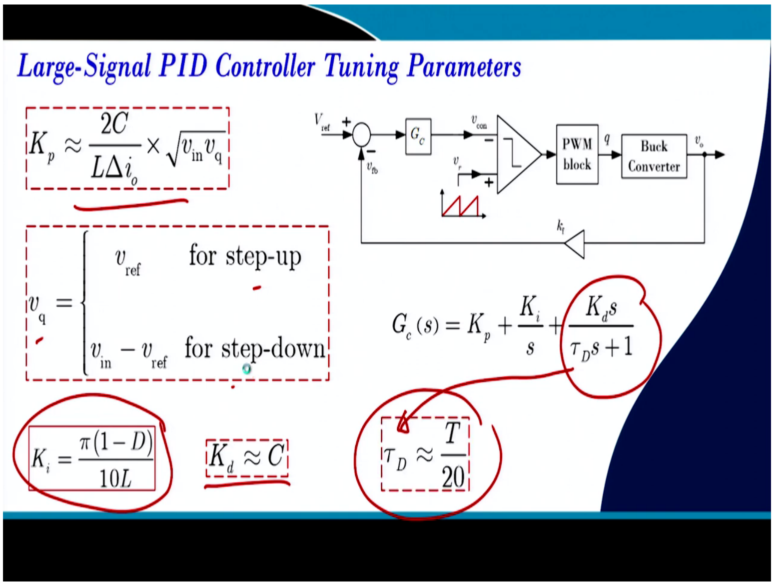

And if you take the PID controller for our you know large-signal tuning, then we have to discuss what should be my proportional gain and what should be my v q for step up and step down we have discussed in sufficient detail in lecture number 50. And then how to set the integral gain from the small-signal model.

Then the derivative gain is simply the capacitor value and then we need to put a band limited derivative. Because of this band limited derivative, the time constant should be much smaller than the switching period that we have also discussed. And we know the voltage mode control implementation output voltage reference voltage. So, it is exactly same as the regular voltage mode control where we are only applying the large-signal tuning ok.

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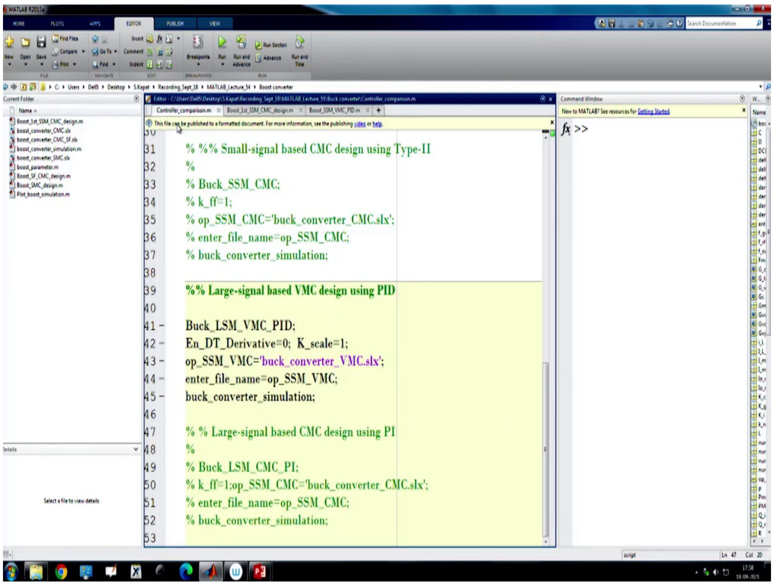

So, let us go to the simulation model and check out the performance comparison.

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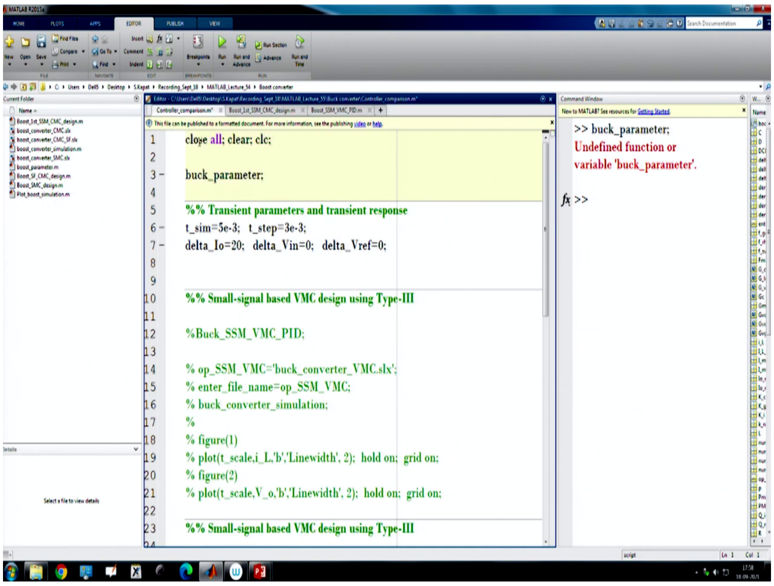

So, if we go to the simulation model, we are applying a load step of 20 ampere ok and there is no. So, we already discussed in our how to interact develop interactive simulation case study and if we run this file. Suppose if you want to run it then undefined so, yes.

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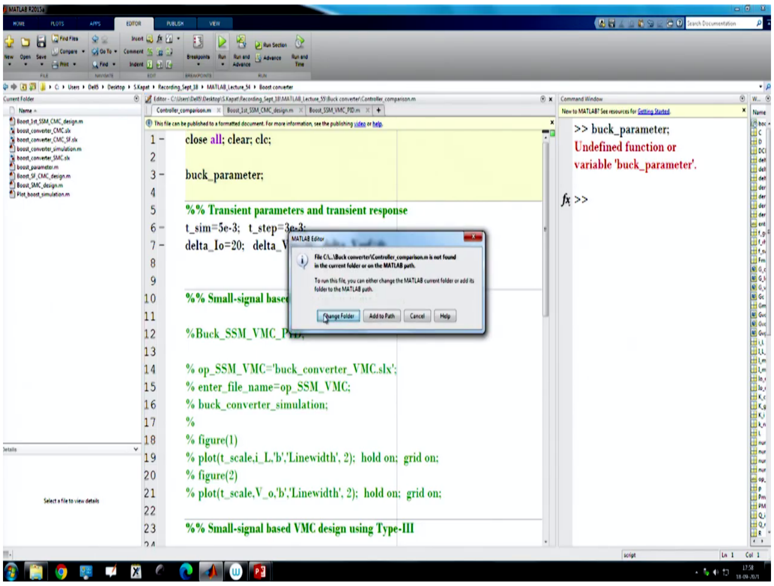

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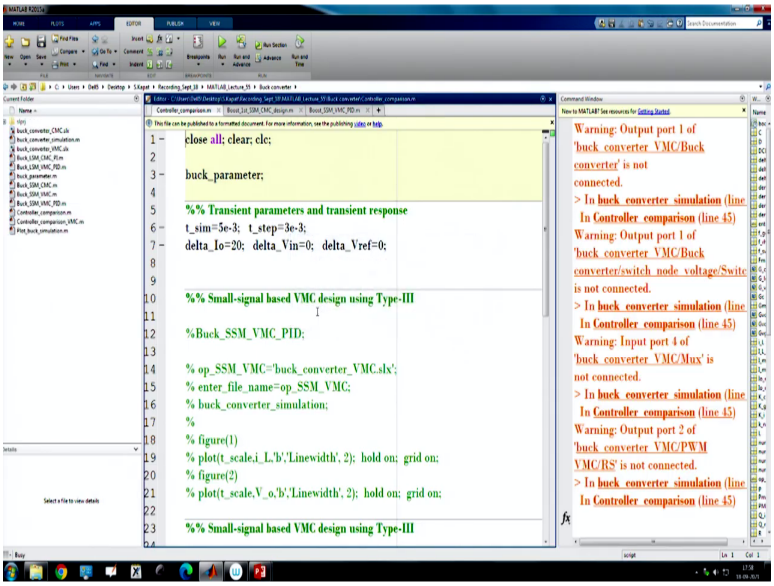

So, it will ask for you need to change the MATLAB ok.

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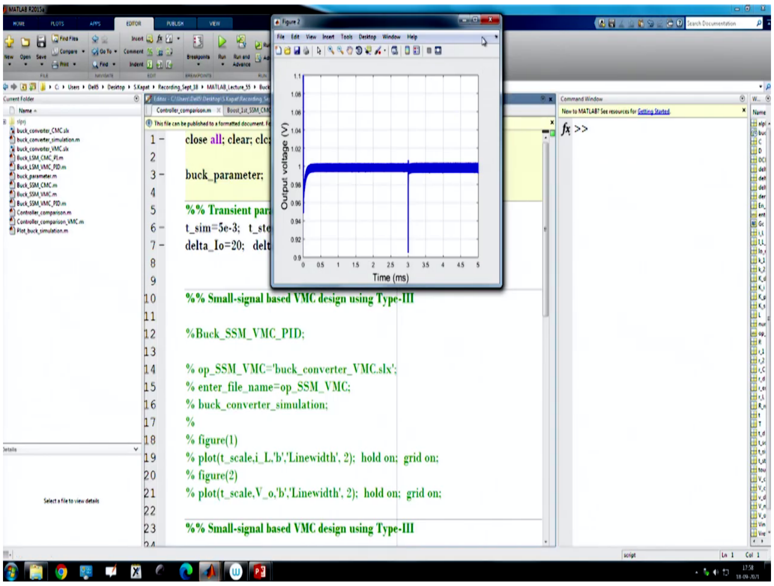

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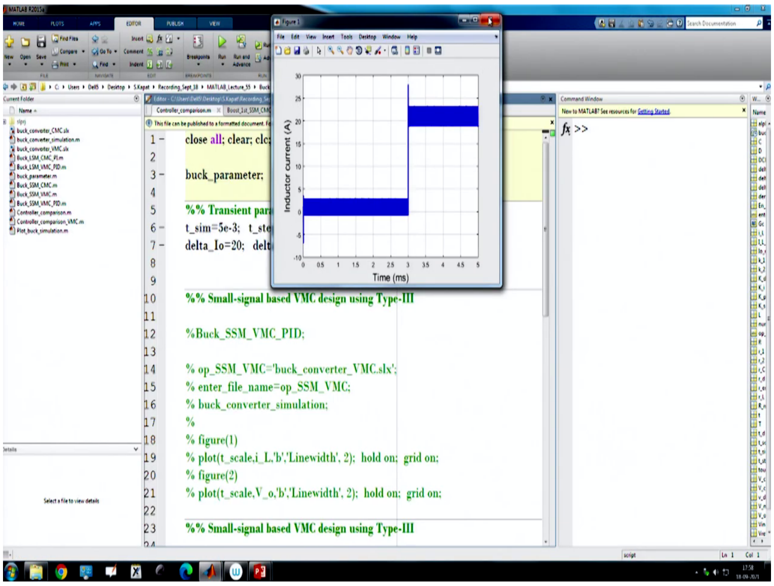

So, let us first wait because we will go one by one.

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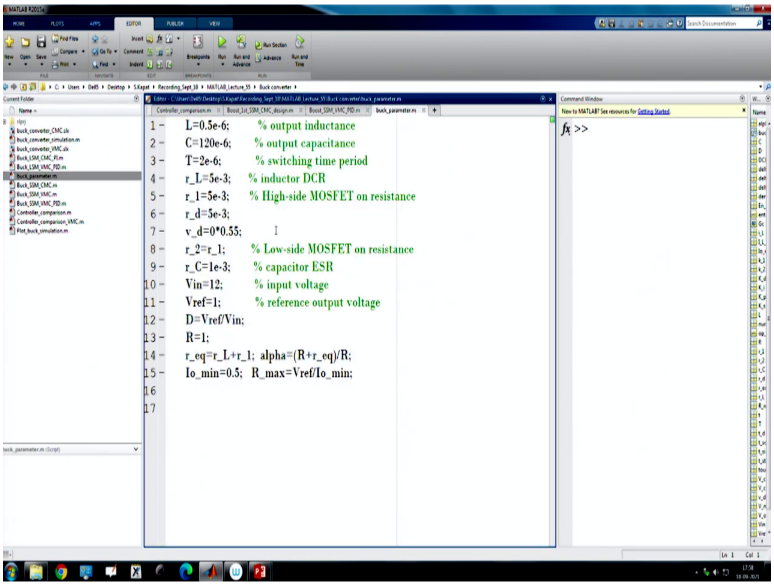

The first thing it will buck converter parameter. It is the same parameter file, which we have been discussing throughout this lecture. There is no change. Next we are considering 5 millisecond total simulation time, 3 millisecond time we are applying a load step transient.

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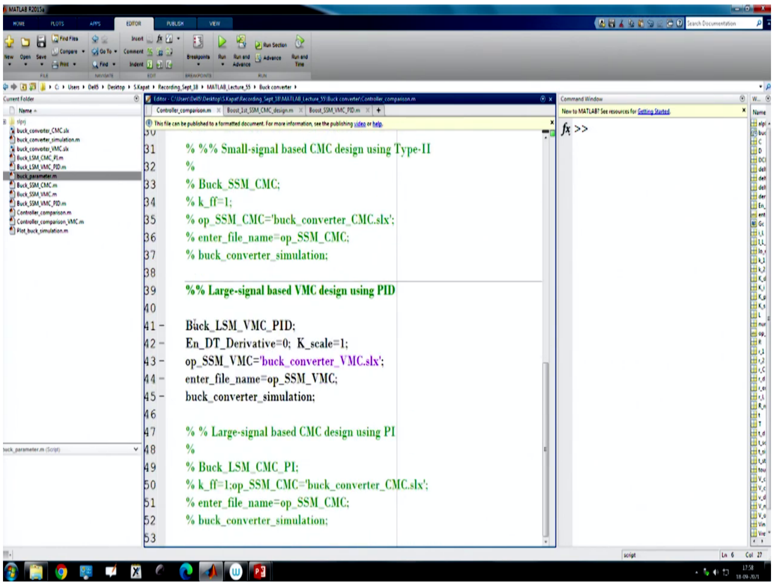

Now, initially what we are considering, ok.

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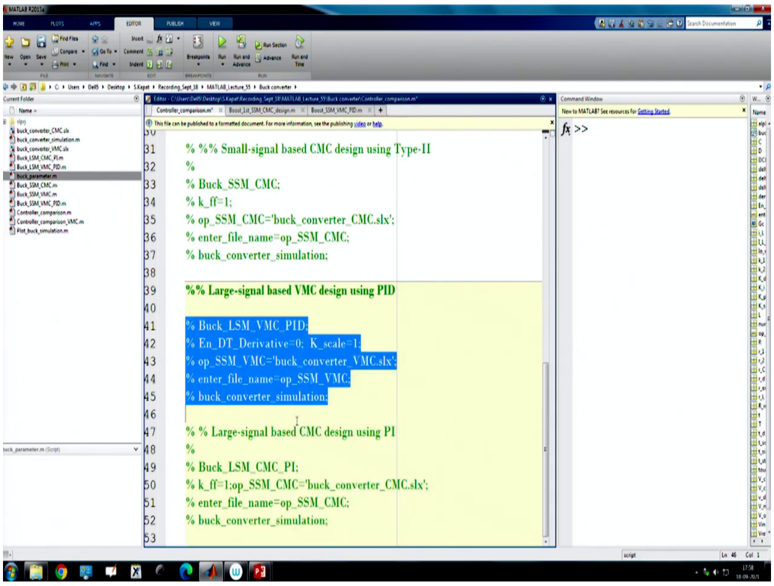

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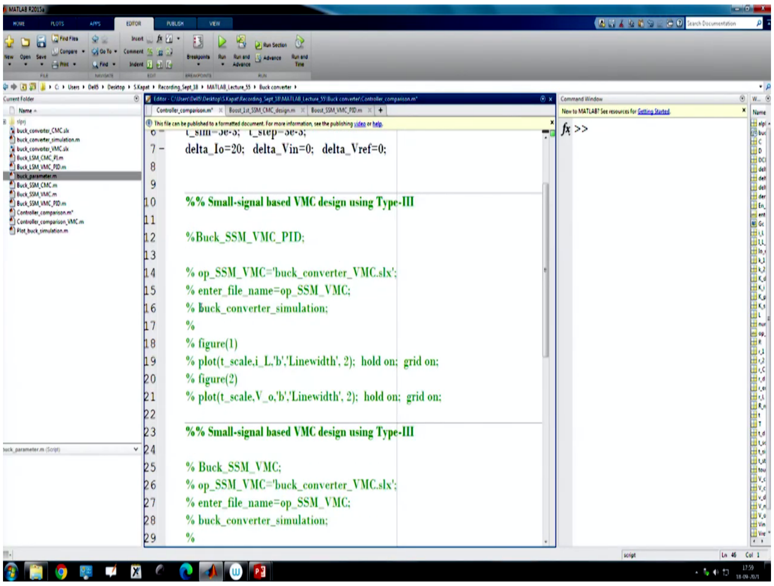

Comment, our traditional we can go for a PID controller also or traditional PID controller.

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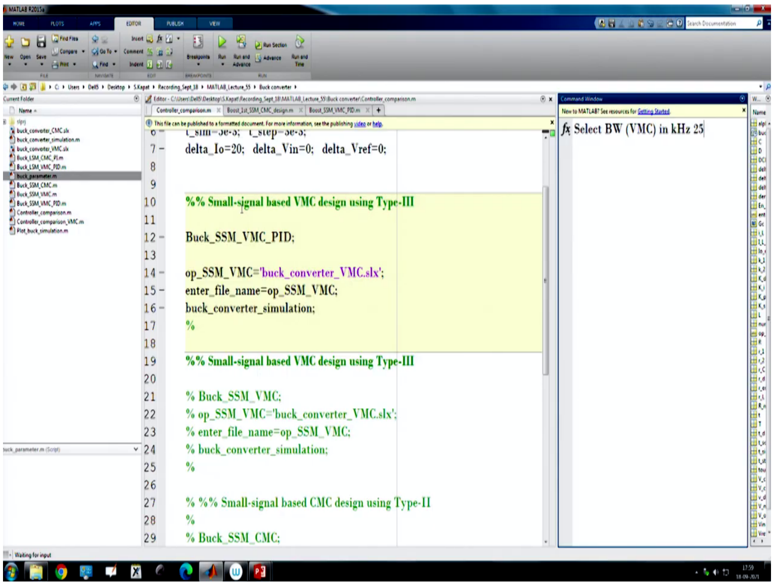

Let us go for a traditional PID controller, where if we run it; it will ask for bandwidth. So, let us say we know that PID controller if you go for one tenth of the switching frequency, then the model may not be valid. So, you can make it like you know, like a 500 kilohertz is the switching frequency.

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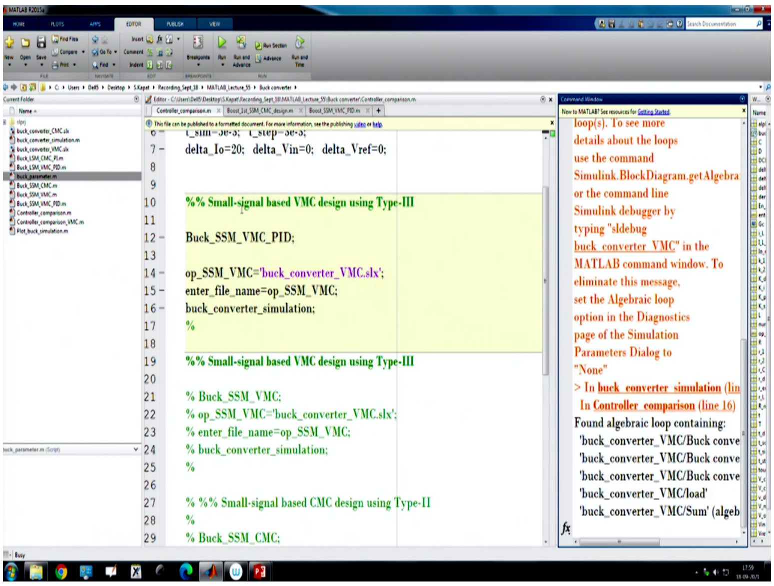

So, you can set let us say 25 kilo, one twentieth of the switching frequency.

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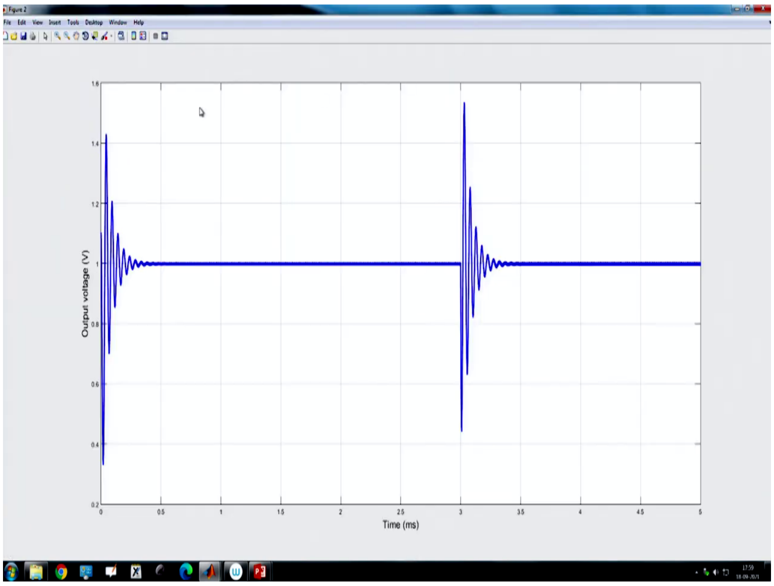

And let us check how does the response looks like. So, response is not at all good because you know it is a large overshoot undershoot and which is not acceptable ok.

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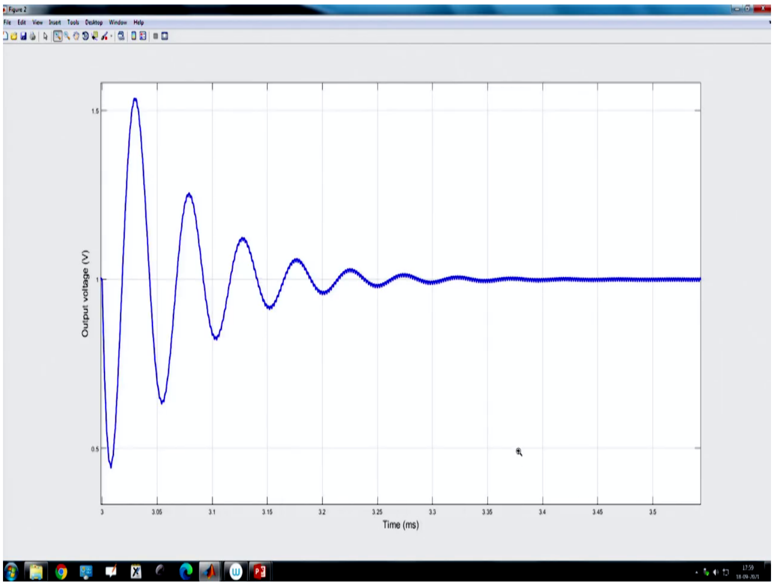

We can improve the response by increasing the bandwidth.

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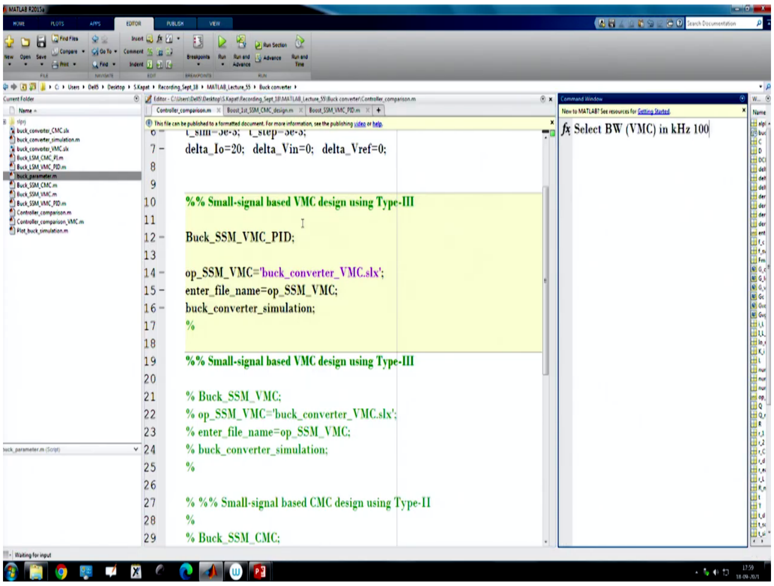

So, you can set. Let us say you know 100 kilohertz.

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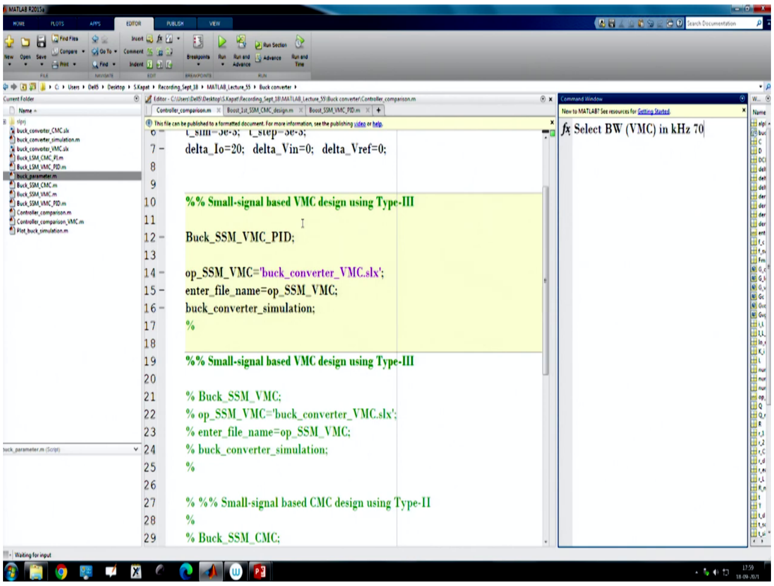

Or 80, 70 kilohertz.

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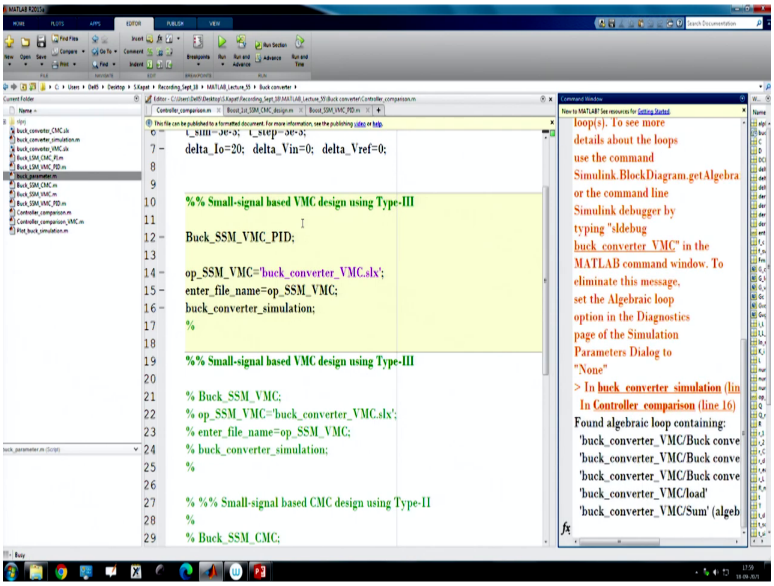

But the model may not be valid.

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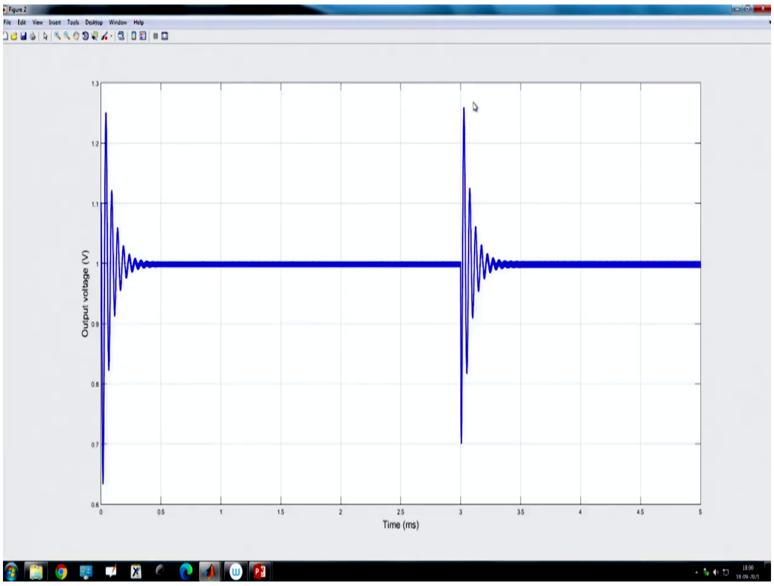

But we can you know. So, we can reduce it, but the question is the model validity remains a question. So, that is why the PID controller we will not talk because the very sluggish response.

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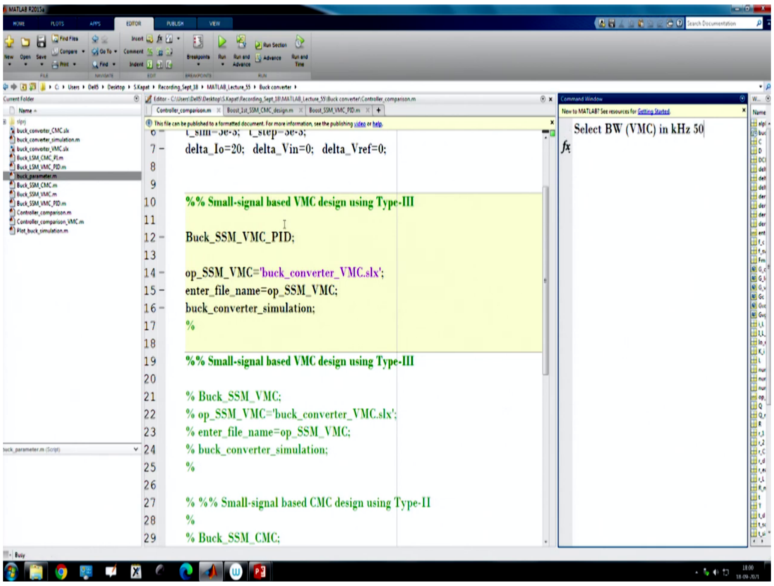

Even if you go up to one tenth of the switching frequency.

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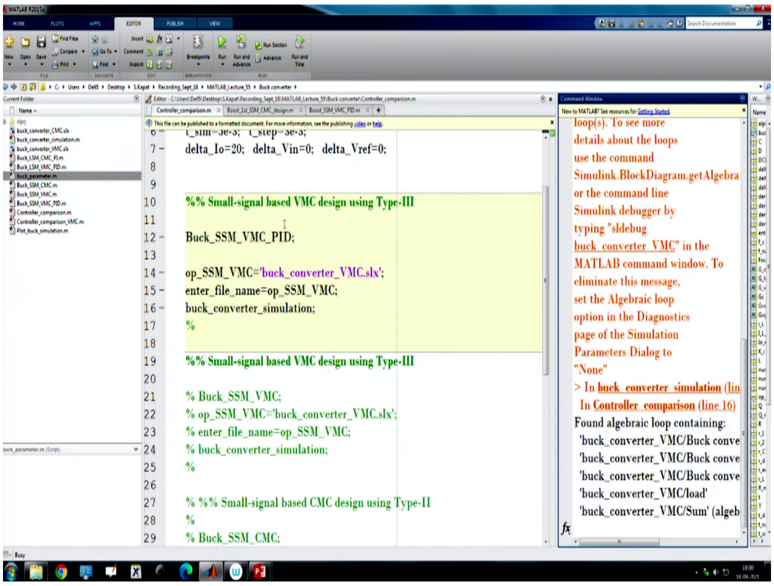

If you go then even the response is not satisfactory.

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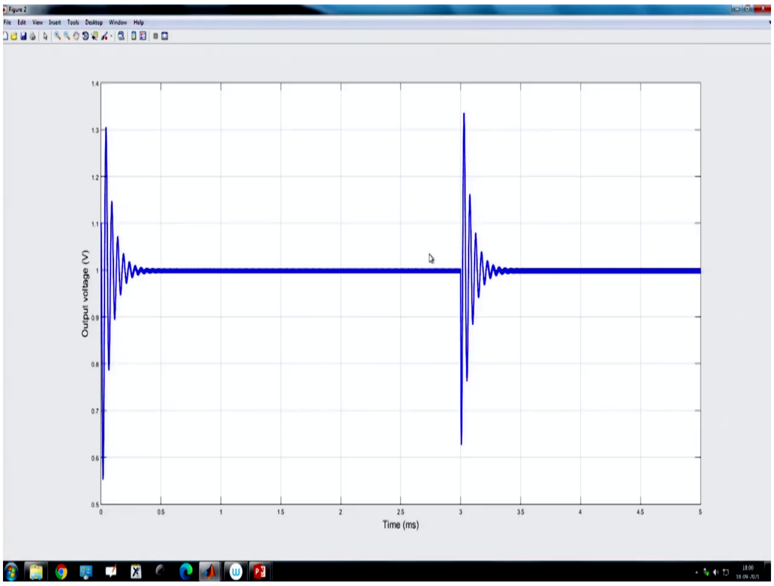

We will hold it the result this is using PID controller in small-signal model.

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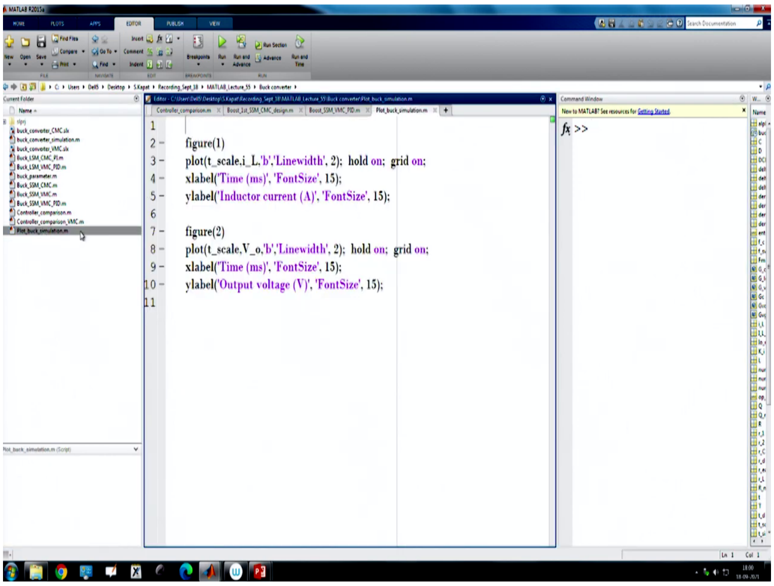

Now, on top of this let us say.

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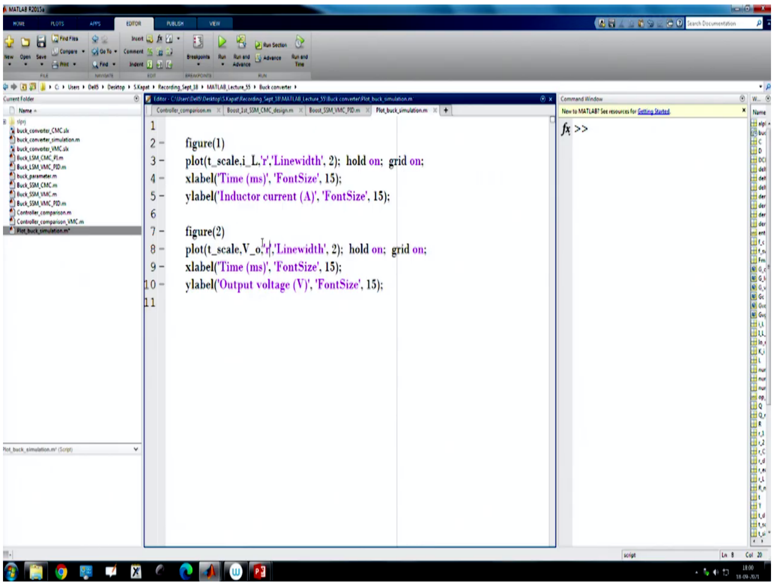

If we use red color, we are going for a type 3 compensator ok. So, type 3 compensator where we are considering.

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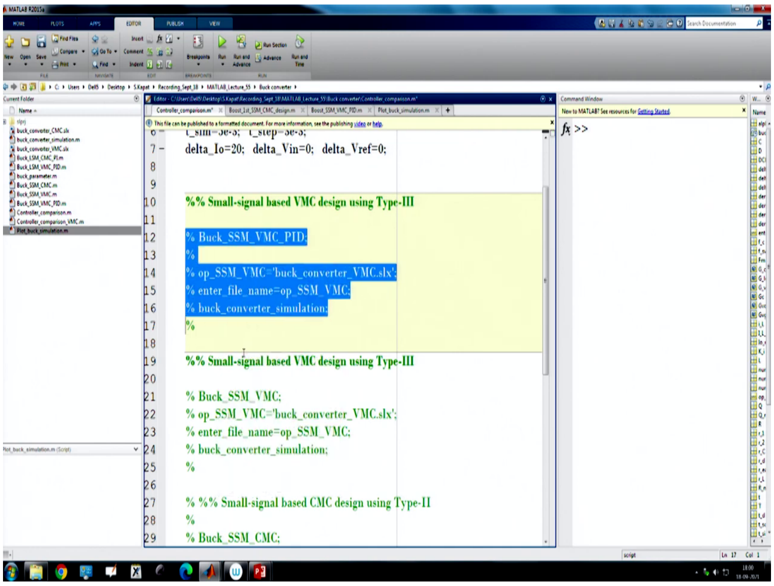

Now, this we have already run comment type 3.

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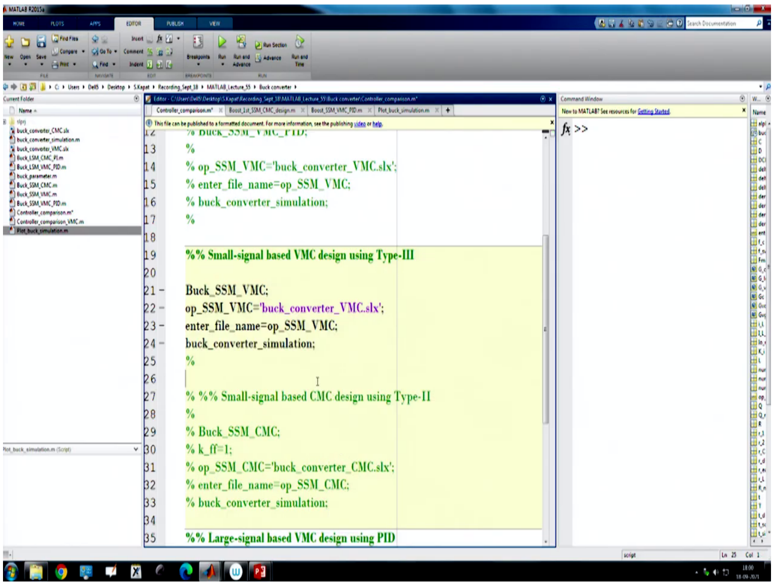

This is our type 3 compensator. So, now we are running.

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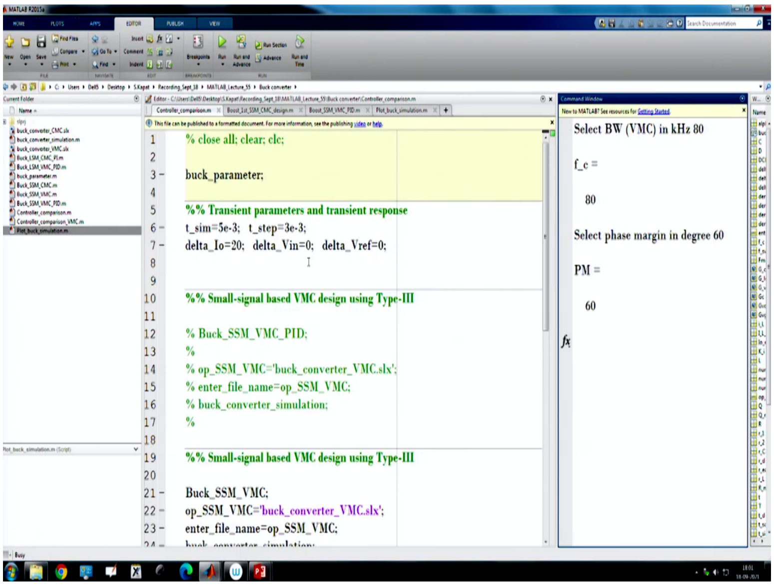

So, we need to hold this ok. So, run it here. We are going to like it can go up to 70 to 80 kilohertz for load transient response. The model still matches fine and band you know gain phase margin is 60 dB.

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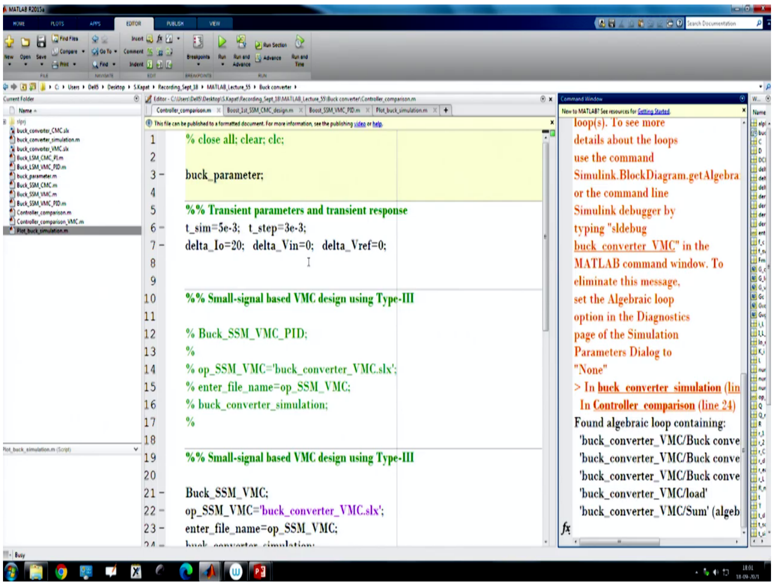

So, let us see how does the response looks like.

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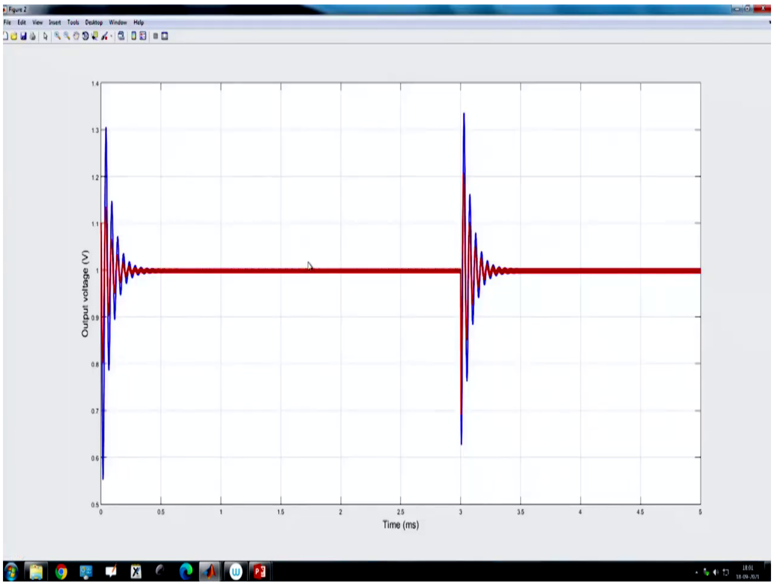

Is this response is much faster because model validity works even for a wider frequency range?

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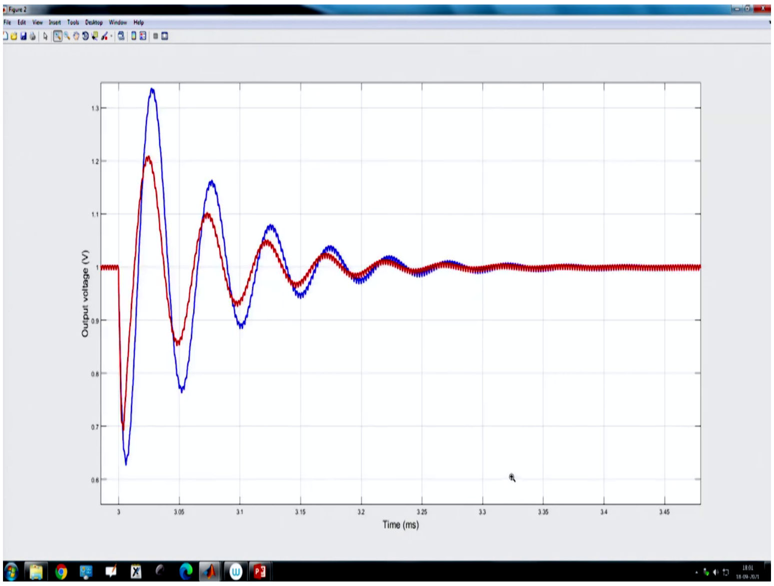

But, still, this may not be sufficient. Now, we are going for large-signal based tuning.

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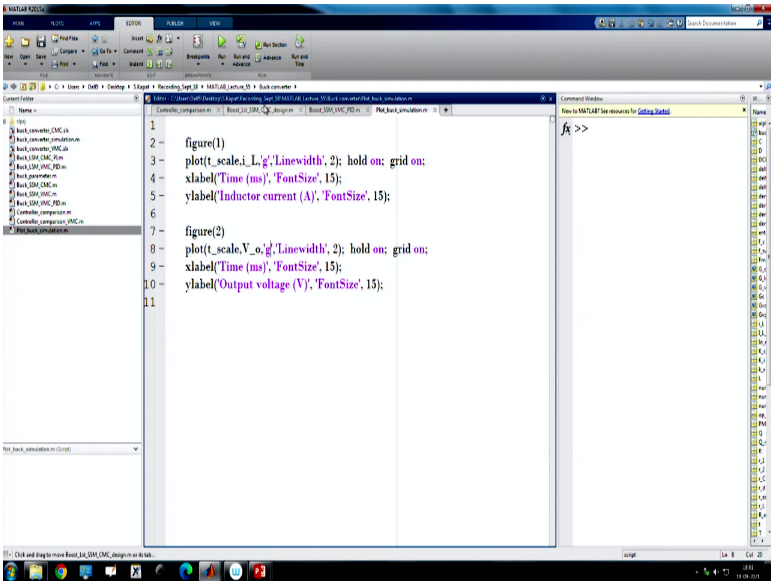

And we are using another color. Let us say we are using magenta or maybe we can use green color for the large-signal based tuning.

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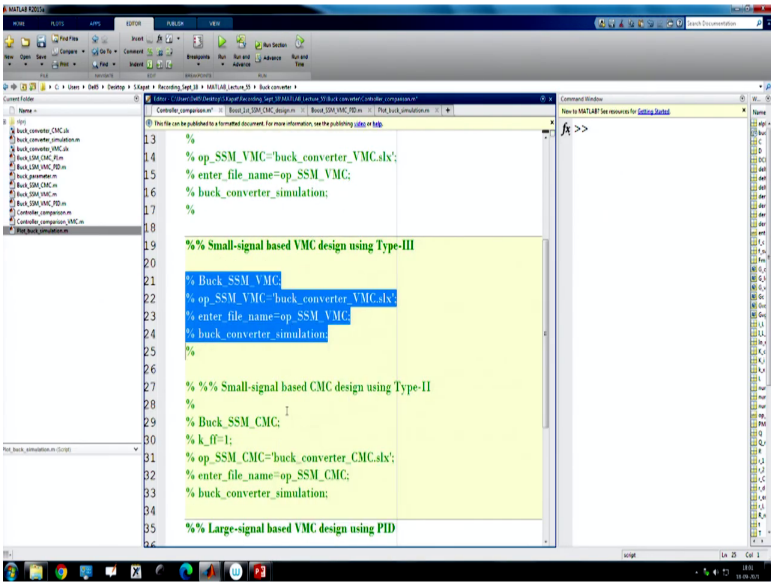

Where we will comment on this particular file, we will comment.

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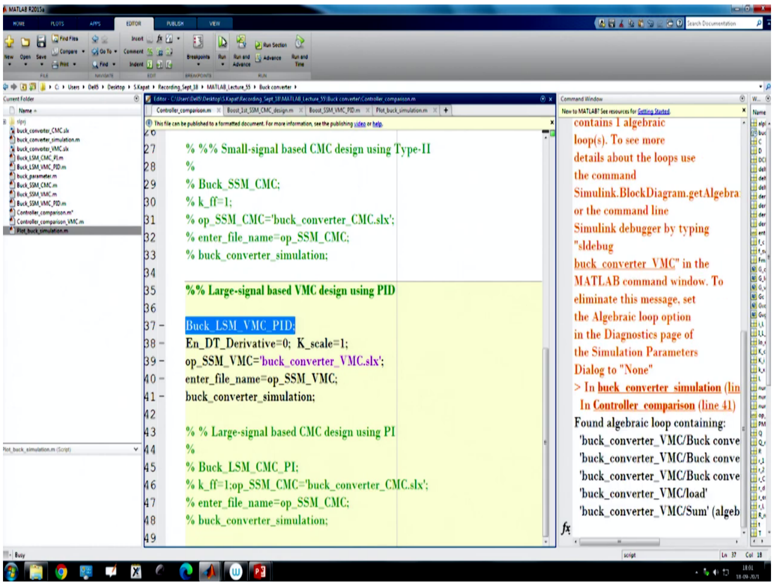

And we are going for large-signal based PID controller tuning uncomment. So, here this function is calling PID controller where all the gains are set accordingly and we have I have shown you all the expression as well as the block diagram. Let us run it and check how does the response looks like.

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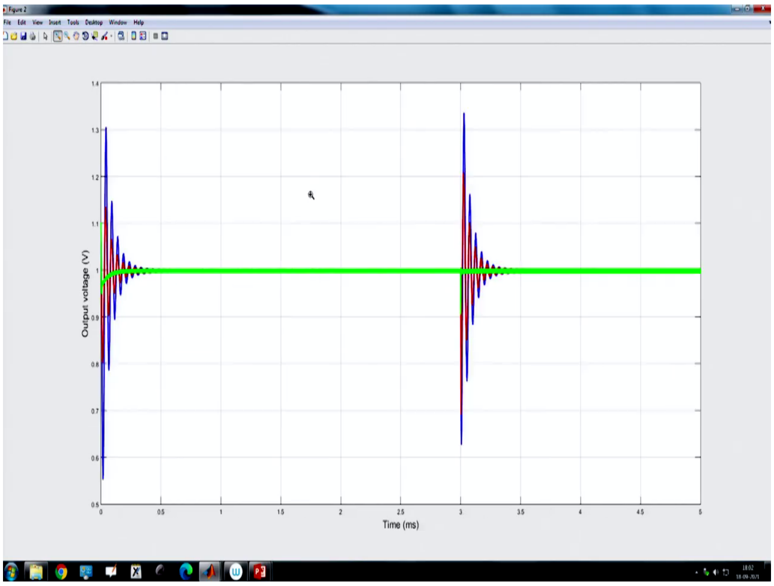

You can see the response is drastically improved.

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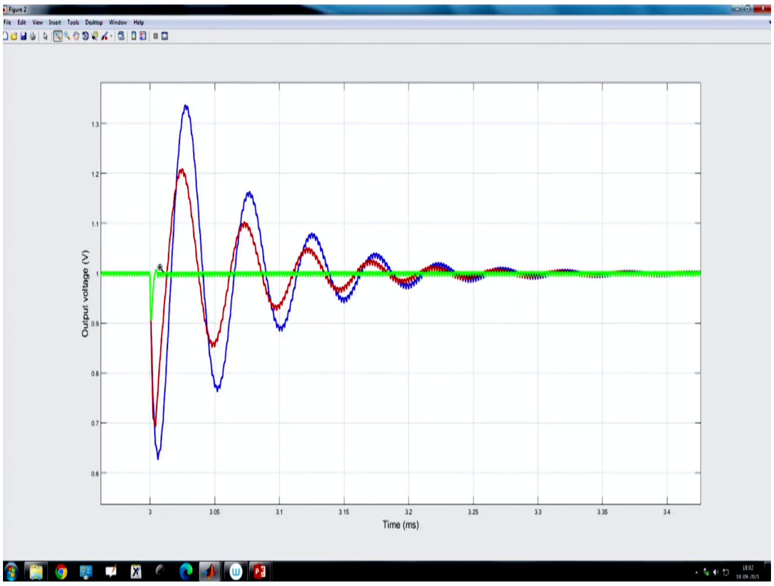

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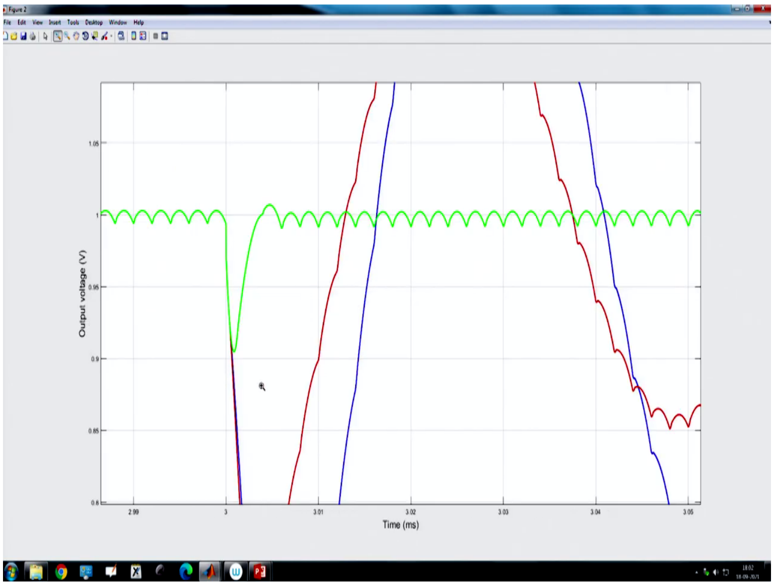

Because the green color it is just around 100 milli volt is the transient response your undershoot less than 100 millivolt.

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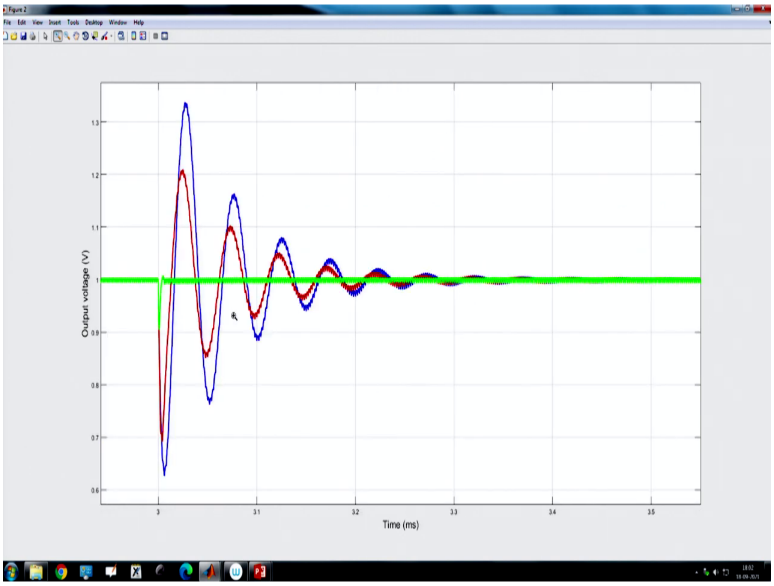

And the recovery time is just a few cycle.

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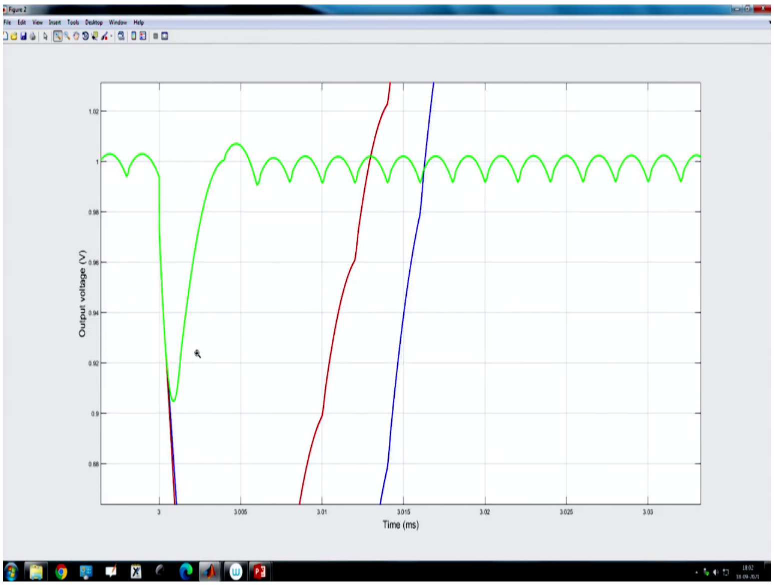

I mean, it is like you know because it is just a two switching cycle whereas, this takes much longer duration.

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And if you go to inductor current you know.

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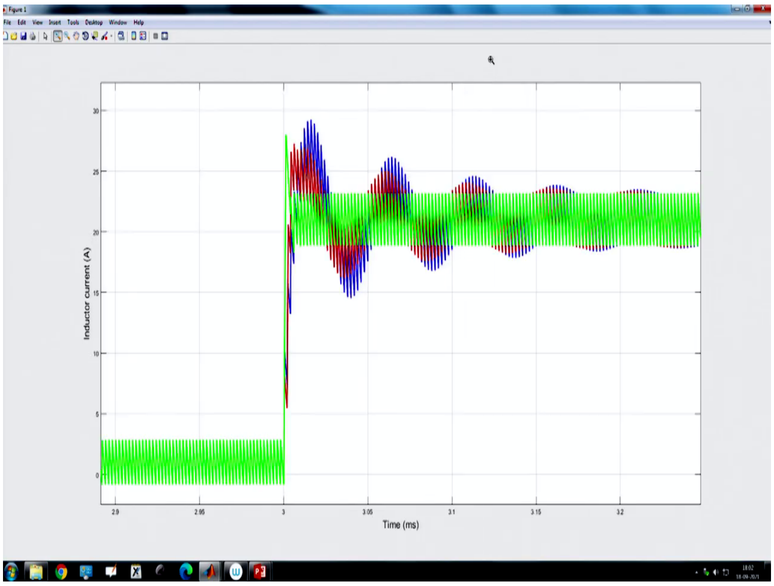

You see, the inductor current is not very significantly high.

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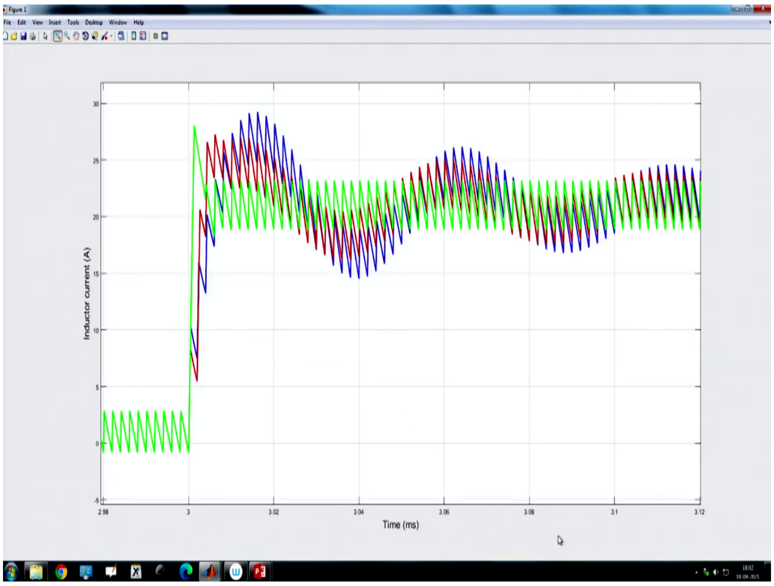

But, our traditional approach of designing because of the model validity and you know small load duty ratio.

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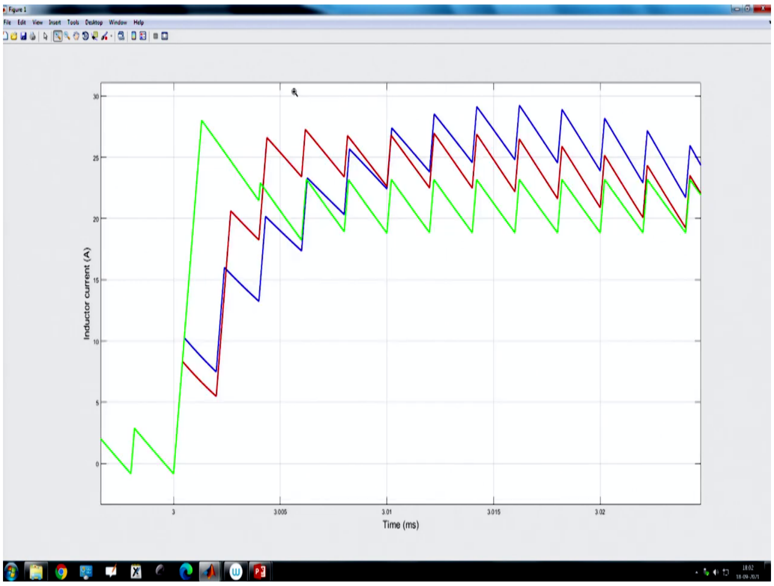

So, you will see the difference will come at the fast recovery time.

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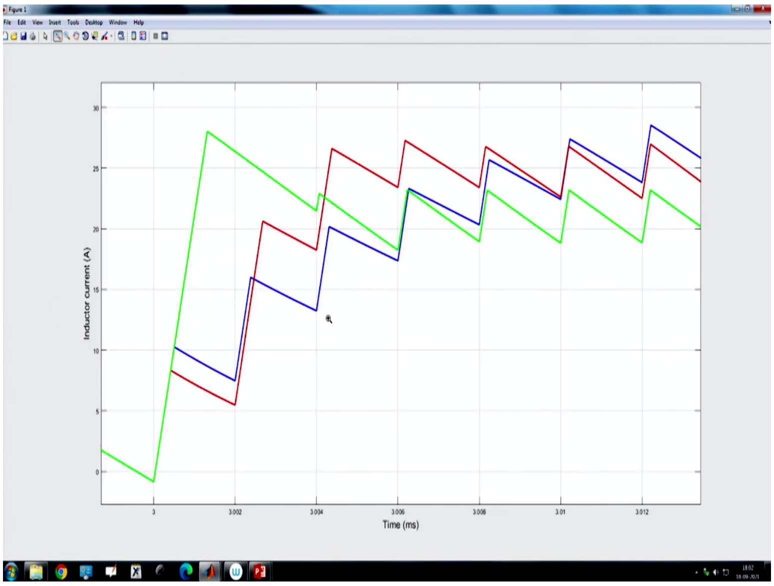

Because since the small-signal requires low duty ratio perturbation. So, during the slew up process, you know there is a turn on of happening and because of that, it will slow down the transient response. Whereas, the large-signal tuning it allow duty ratio saturation. you see it is turning on for a quite some time and then turning off and it is coming to next operating point in almost one switching cycle. So, it achieved almost time optimal recovery.

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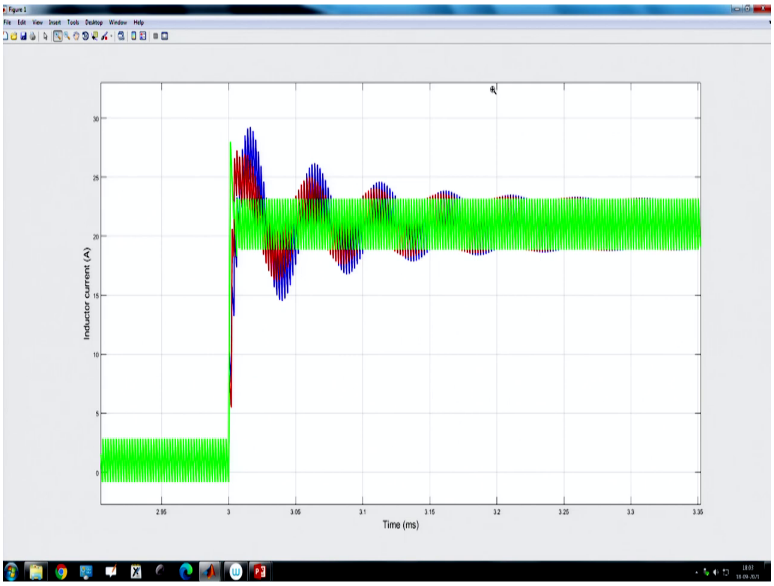

So, now, this large-signal tuning can drastically improve the transient performance compared to the four small-signal tuning. Now, we are going for current mode control. So, let us you know close all the files and we will again clear once more.

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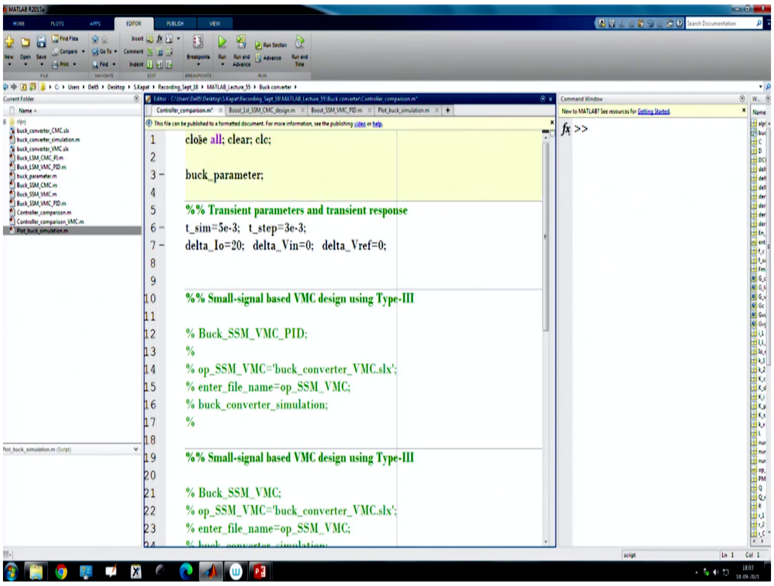

Now, we are going for current mode control.

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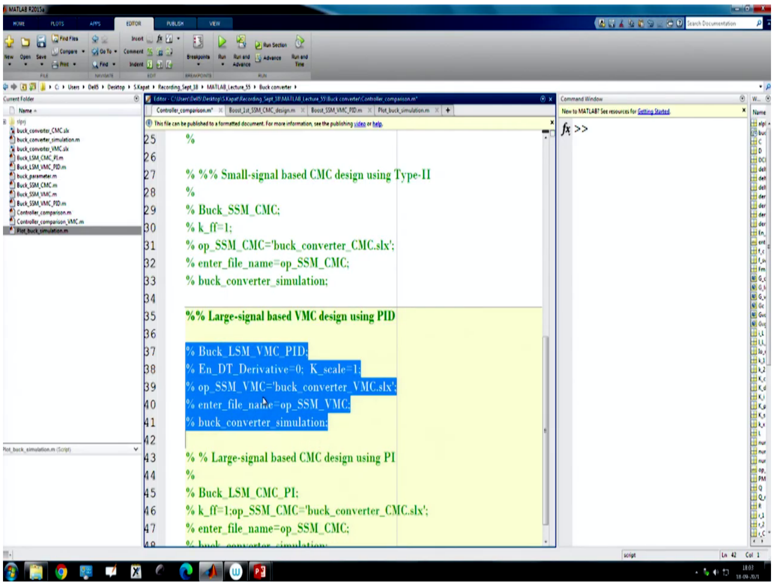

So, in current mode control you know we will see two things.

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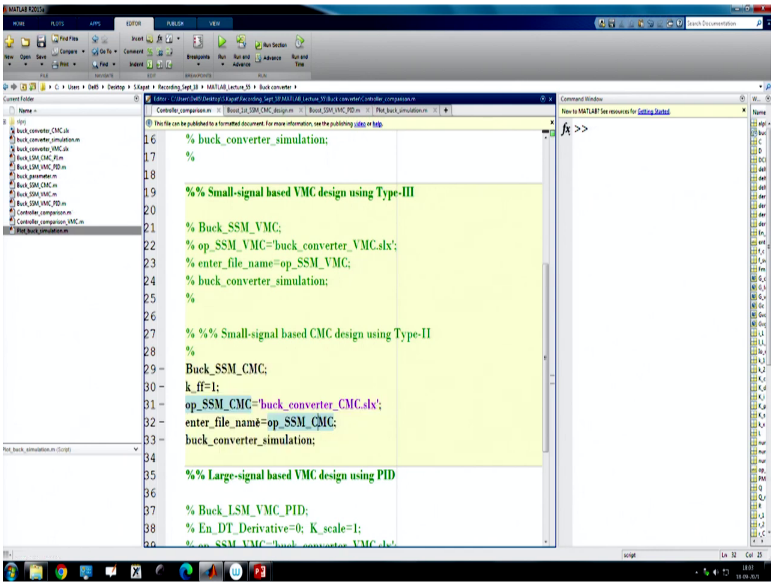

The first thing first we will go for small-signal based current mode control. So, here k ff I have shown you if you go to the k ff the k ff if you go to current mode control. So, this is a load current feedforward. So, if you set k ff to be 0 then you are not considering load feedforward ok. So, we will consider cases first k ff equal to 0.

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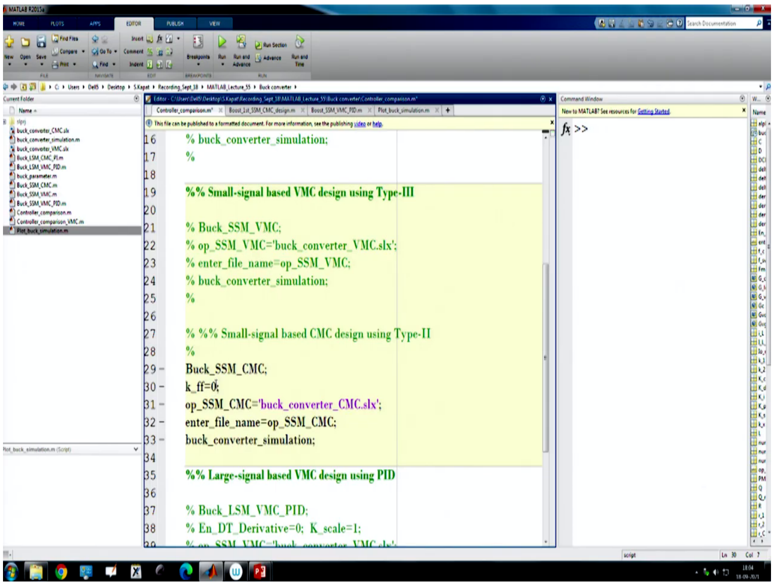

So, in this case, we are talking about let us say we are using blue color.

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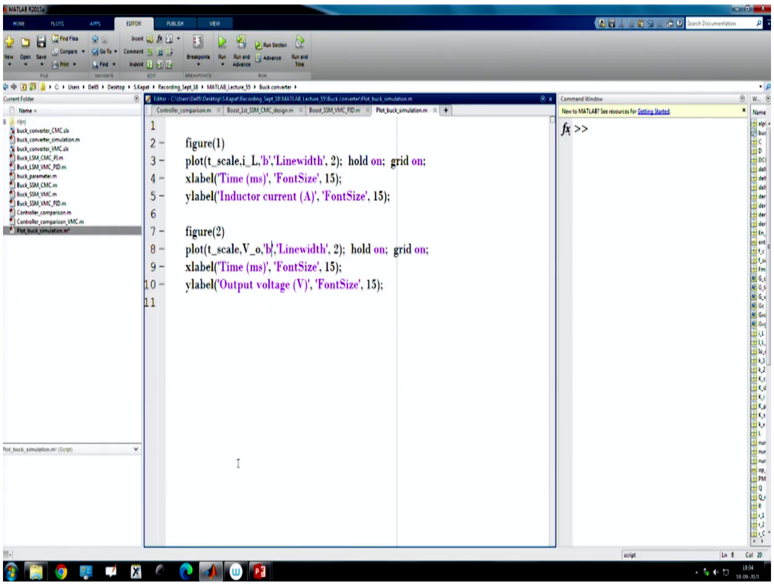

So, the regular current mode control design ok. So, let us run it using the regular current mode control design.

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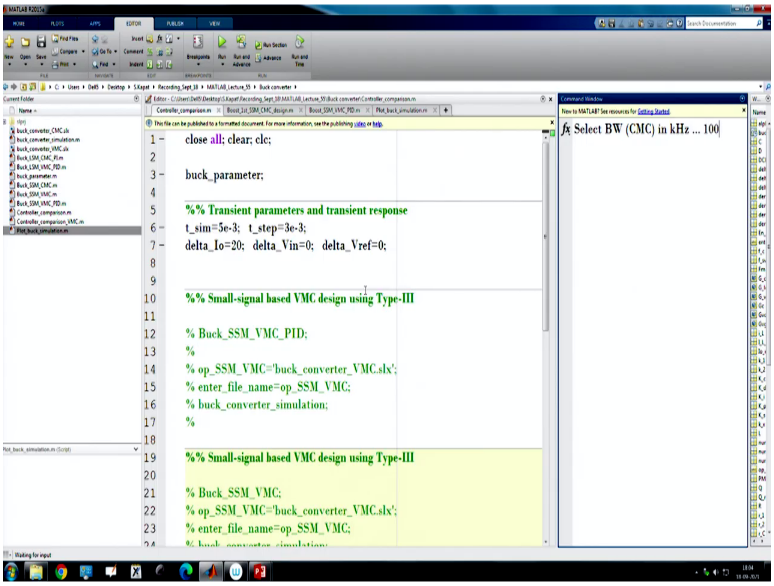

So, if you run it; it will ask for bandwidth. So, let us say we can go up to let us say 100 kilohertz.

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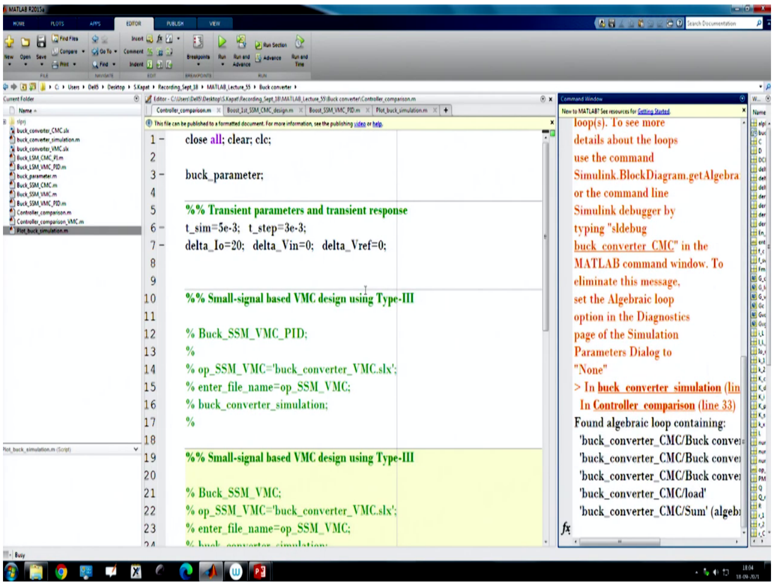

Close trying to go close to one fifth for load transient somewhat we can go, but I think this still model matching will be a concern, but we are trying to go close to one fifth. Let us see what happen. So, this is a load transient response using current mode control.

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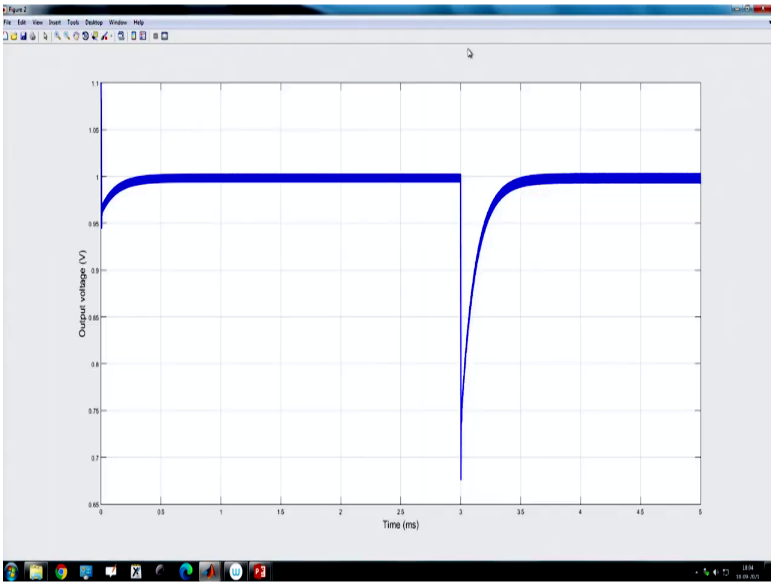

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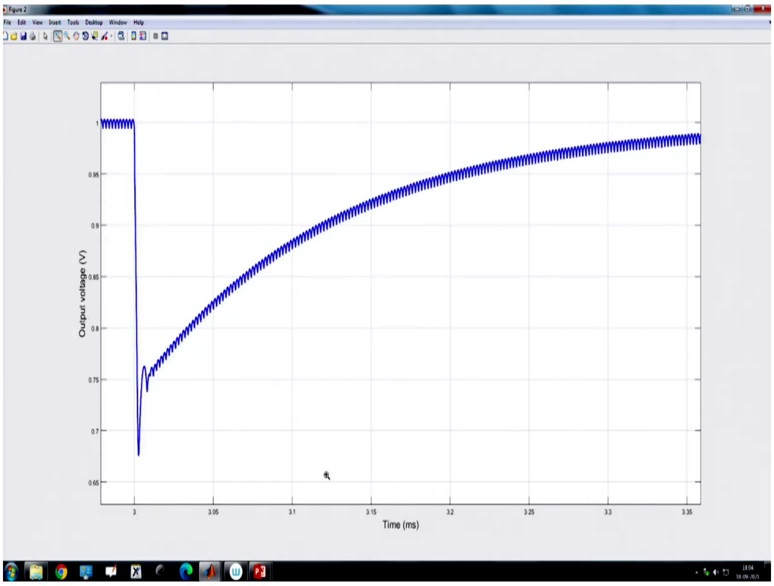

And this is a response and you see this we have discussed the model matching will not happen due to the jump.

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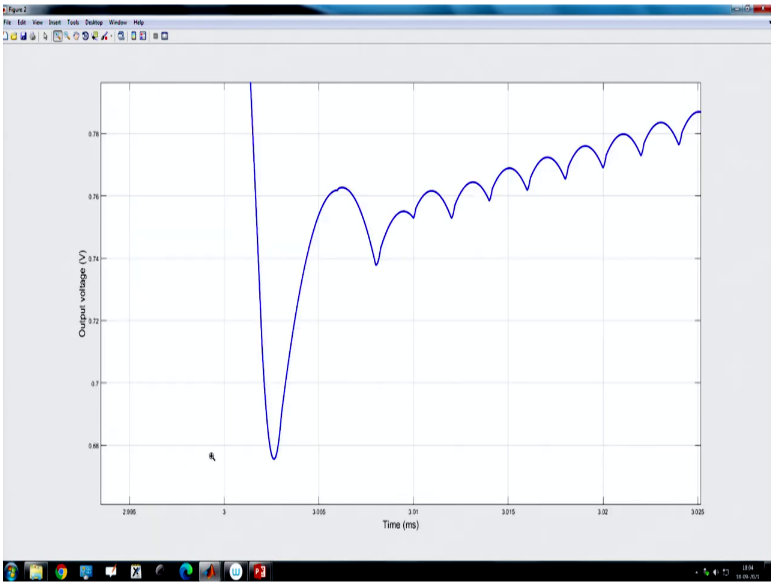

So, it should not go to one fifth.

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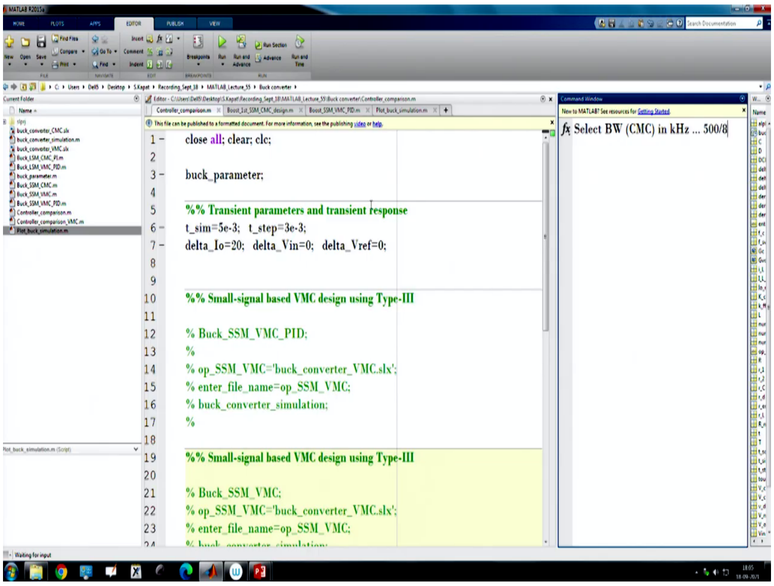

So, let us limit our whole thing to one eighth.

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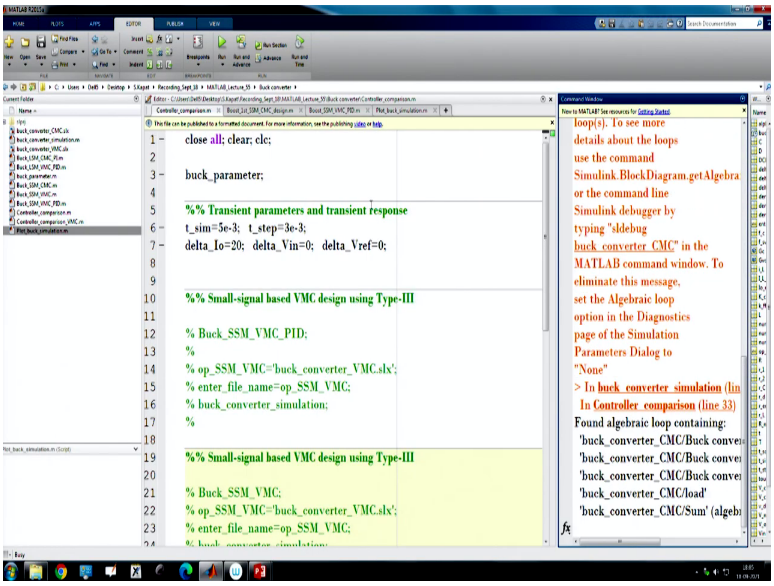

That means we will get 500 by, let us say one eighth.

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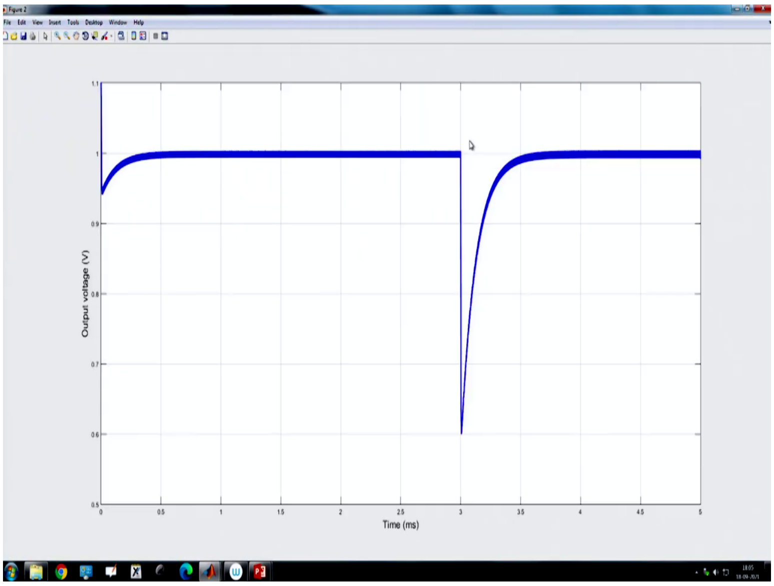

And if we say the response; so, now, there is no as such very large overshoot fine.

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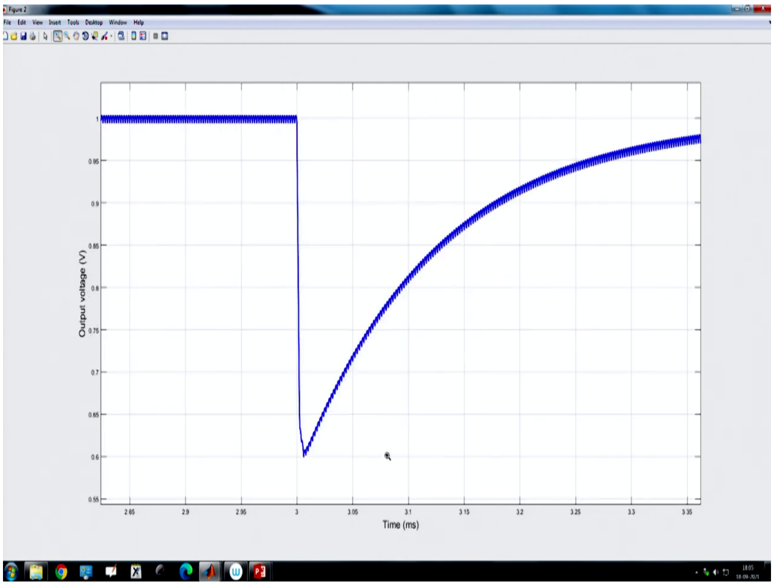

So, it is a sluggish response ok, but unlike in voltage mode, there is an overshoot undershoot. It has only undershot, but it is slow. Now, if you consider on top of that load current feedforward.

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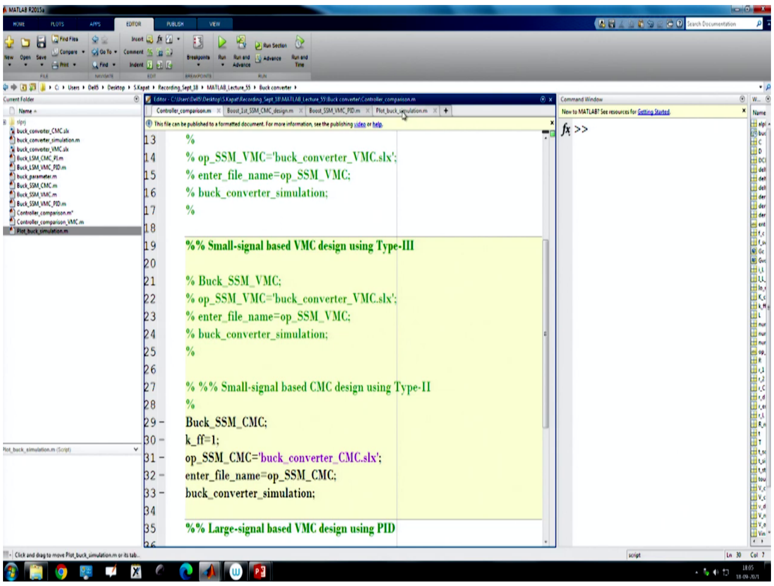

That means we are considering 1 and we are using a different color.

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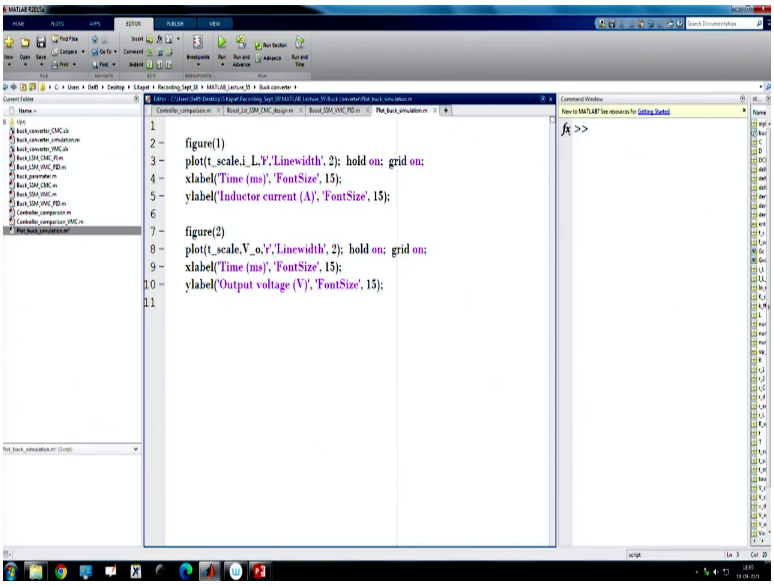

Let us say we are using red color and let us run it. So, if you run it.

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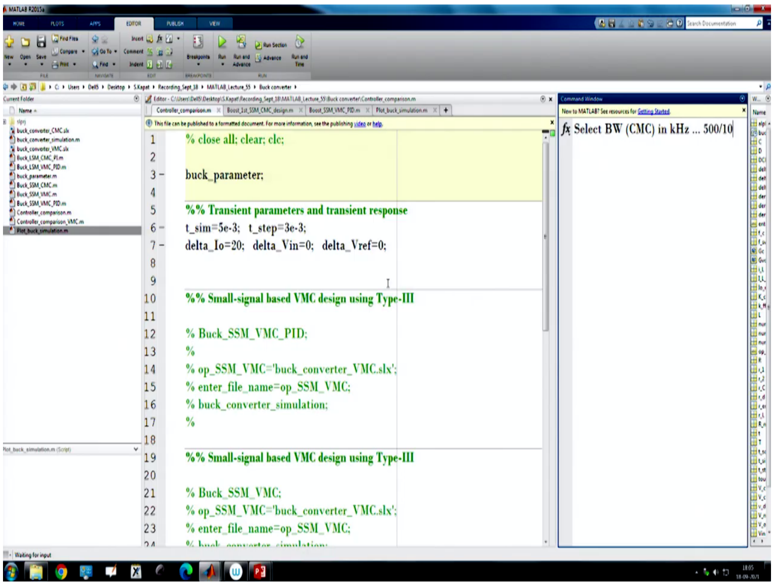

We want to hold it then. So, here also we are you know, 500 divided by so, let us go on 10.

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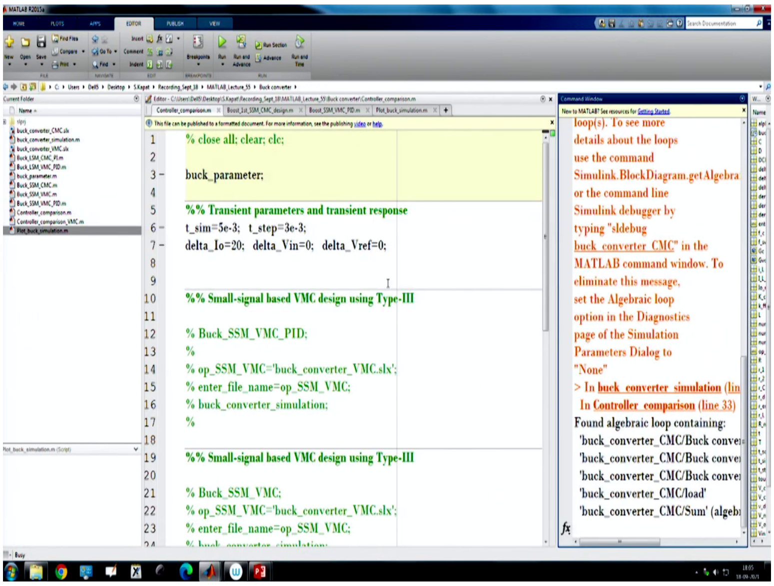

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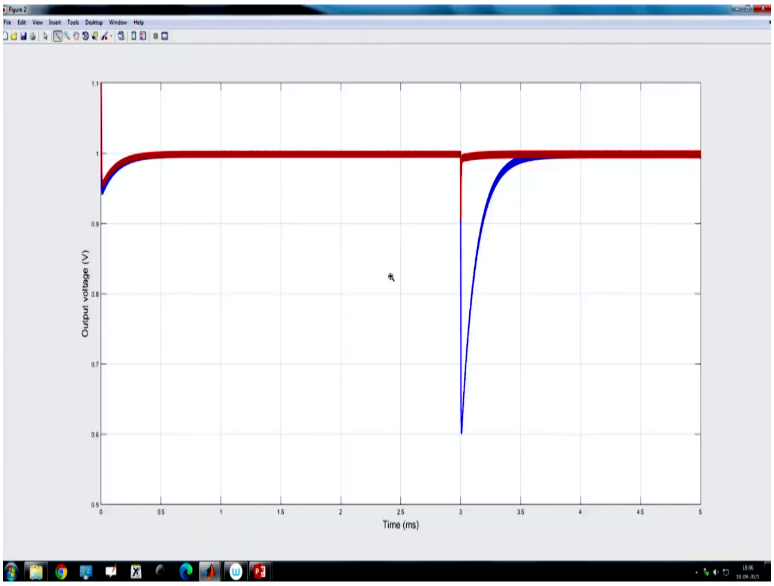

And see it is much faster.

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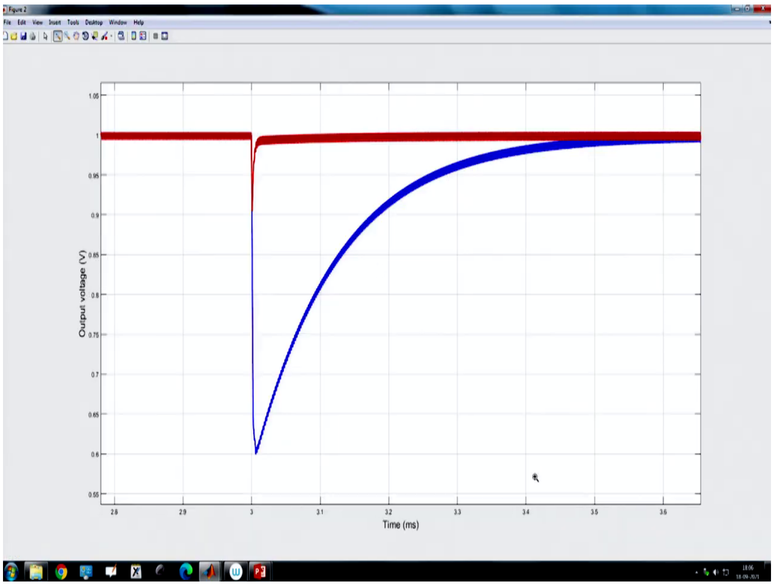

Because we have incorporated the load current feedforward.

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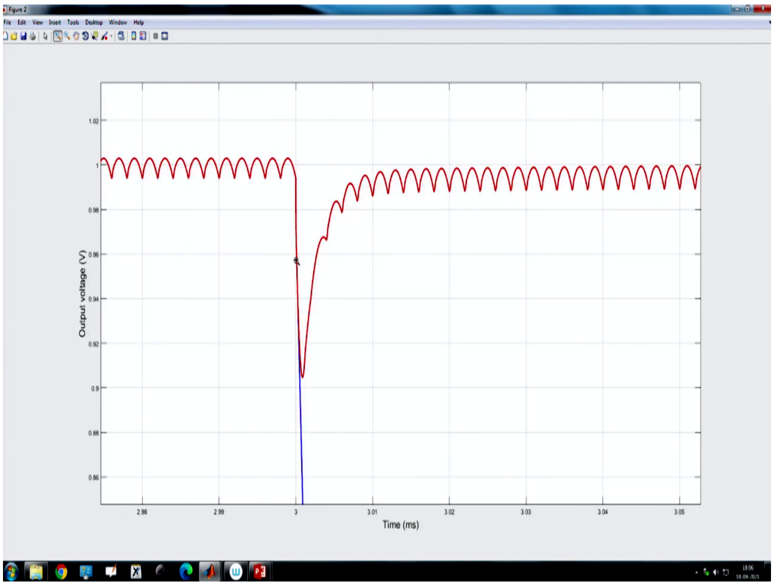

And we have discussed the load current feedforward can drastically improve the performance right. Now, we are going to large-signal tuning ok for current mode.

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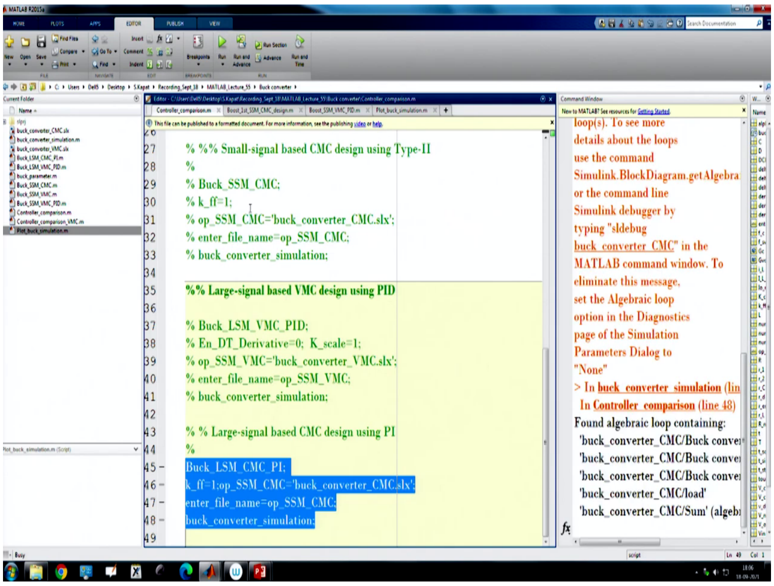

Where we need to incorporate loads, load current feedforward and we discuss that we can use load you know we can estimate the load current or we can use a physical sensing right.

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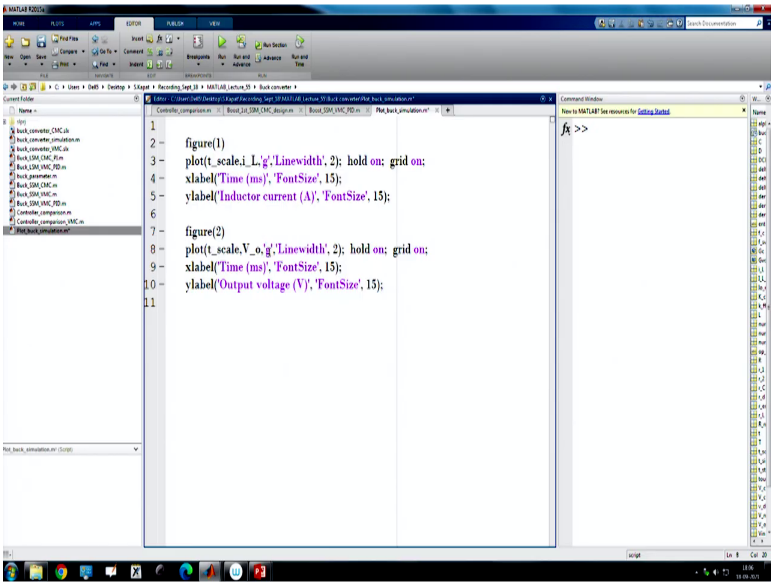

So, estimating load current is a good solution in digital control solution. So, let us do that and we will run it now using green color.

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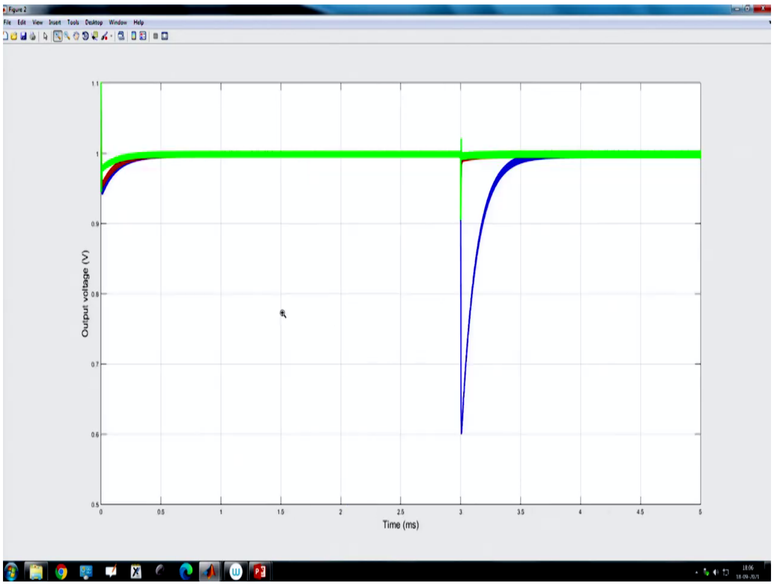

And see what happens yes. So, you see.

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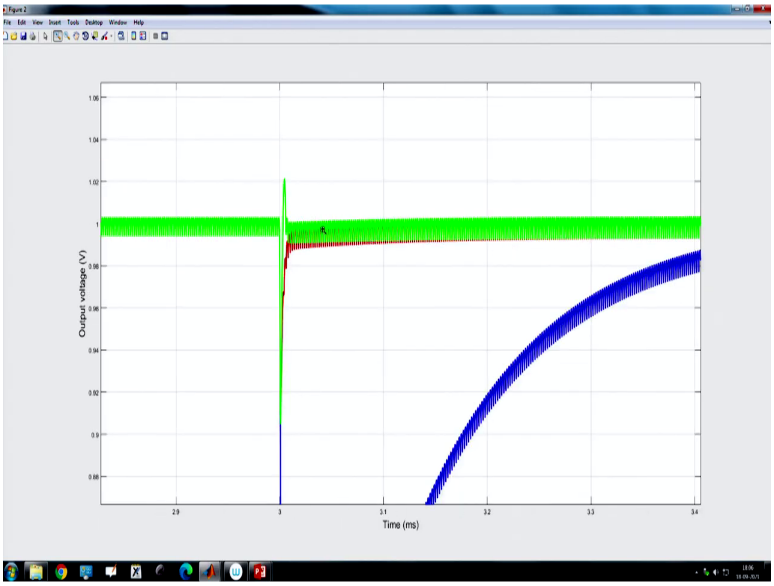

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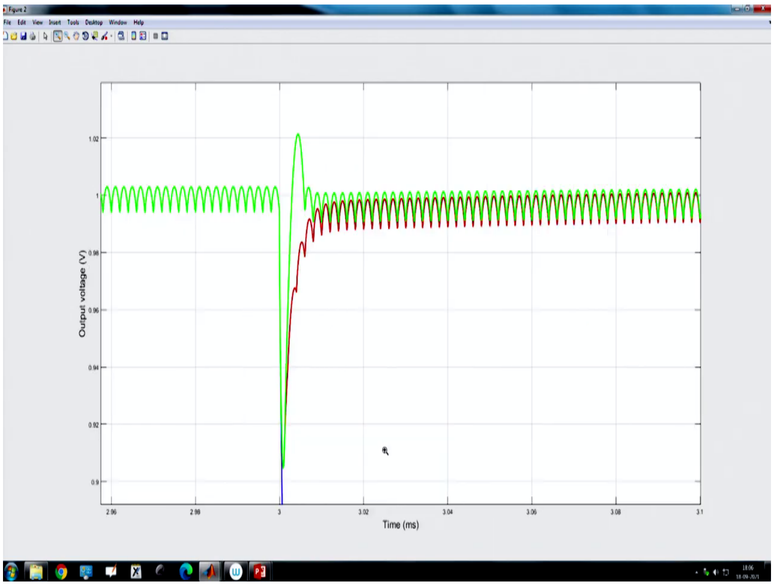

When we consider our tuning.

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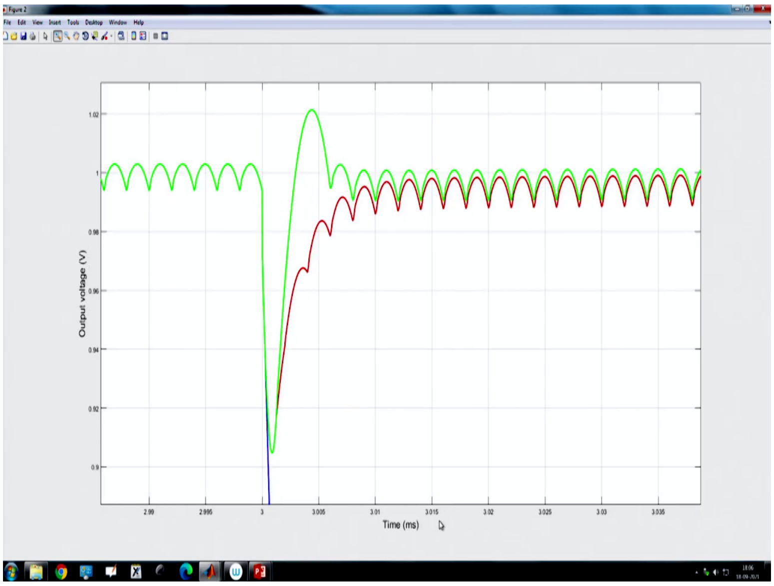

Large-signal tuning it is recovering in almost three cycles whereas, load feedforward is taking some more time using the regular current mode control with load feedforward.

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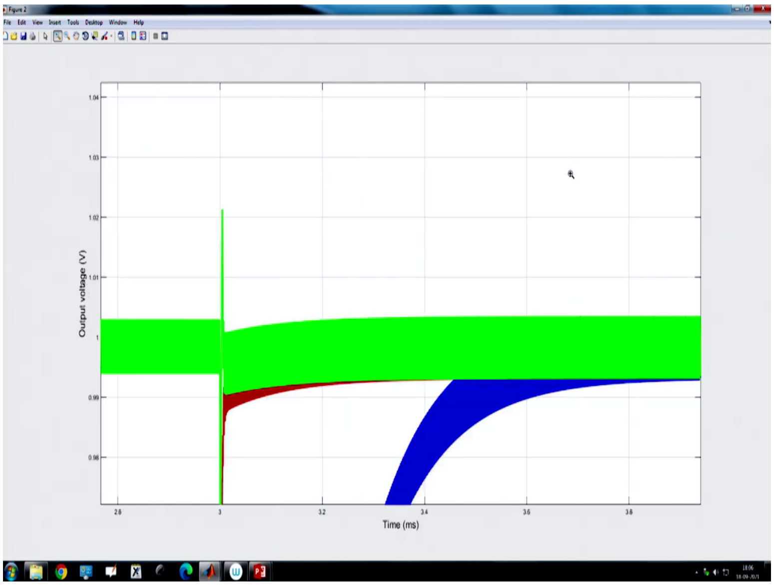

And it is somewhat sluggish respond.

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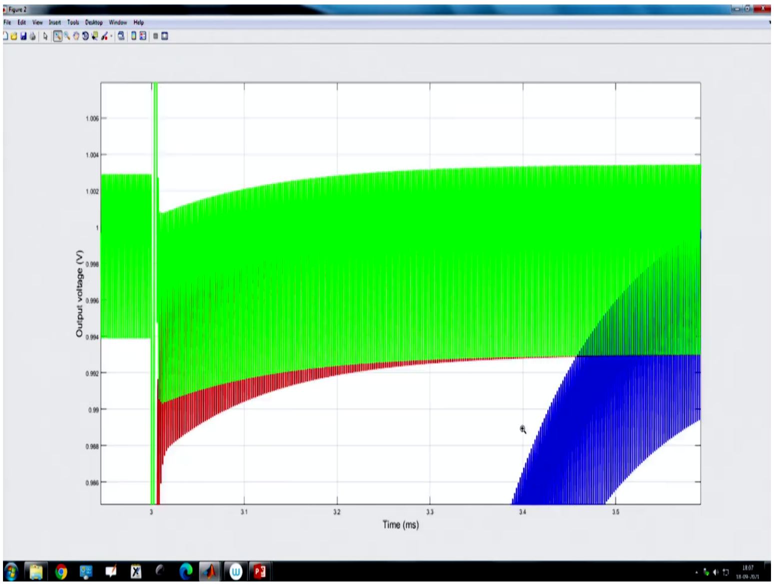

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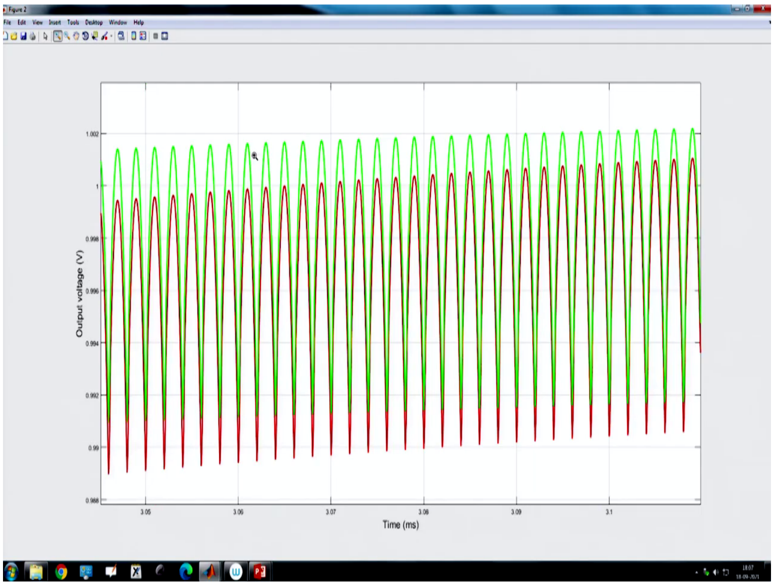

So, it takes few more cycles to reach steady state ok. But, it is good that both are giving fine with load feedforward.

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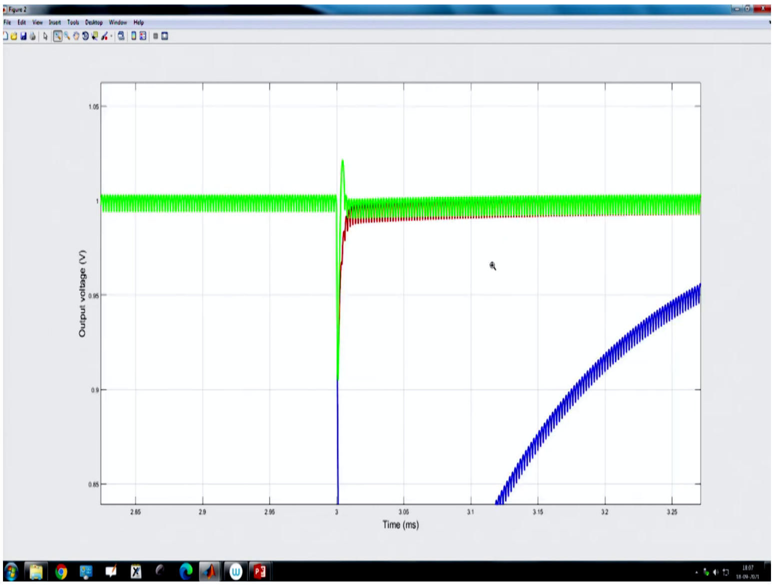

But, optimal gain makes it even faster right.

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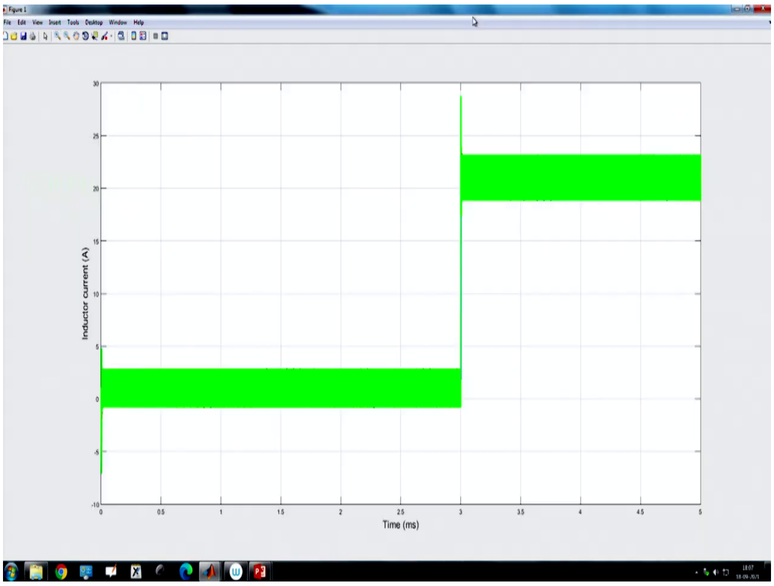

So, you can just check it here.

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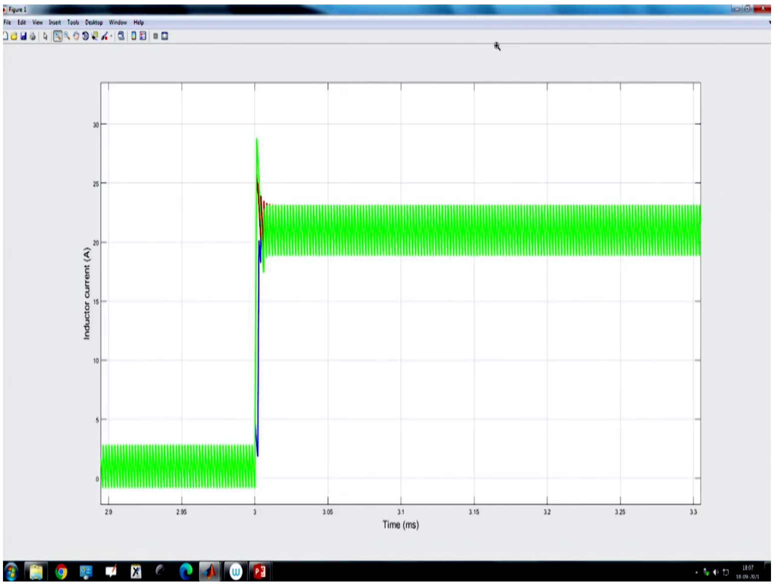

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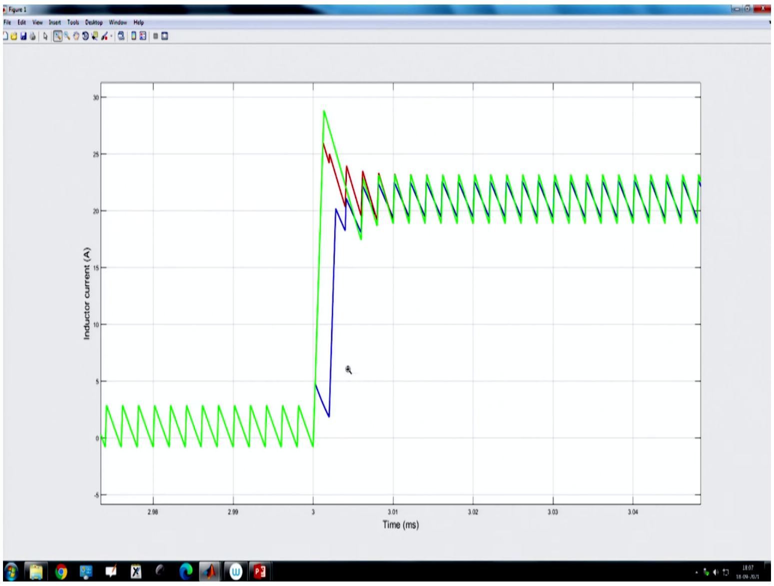

So, these two are the responses.

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But, because of load feedforward it is allowing the duty ratio to saturate. So, that, but in regular current mode control because of on off operation it is slowing down the transient performance and which is quite obvious and that we have discussed. So, we have discussed PID tuning, large-signal, small-signal for voltage mode current mode in all case studies.

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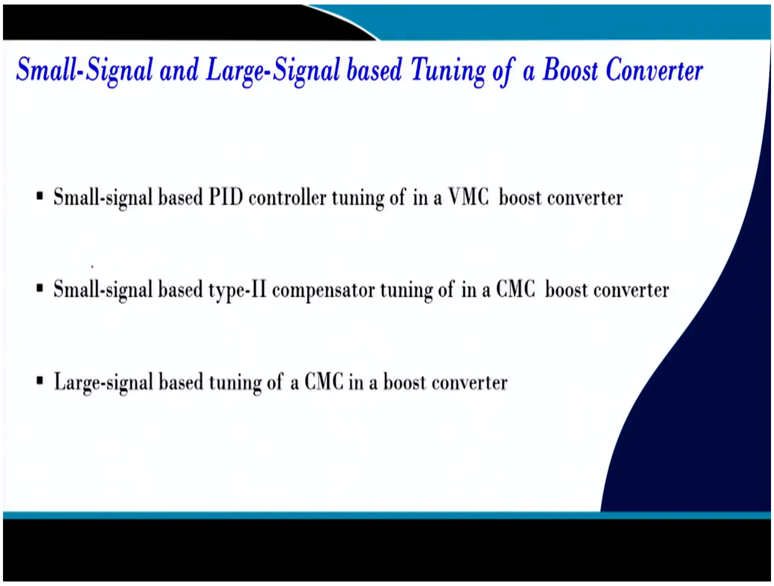

Now, we are going to consider a boost converter. So, in a boost converter, we are going to consider reference transient using small-signal as well as large-signal ok. So, let us go now we will just stop all this waveform. So, let us go to our boost converter case study, ok. So, we have to consider buck.

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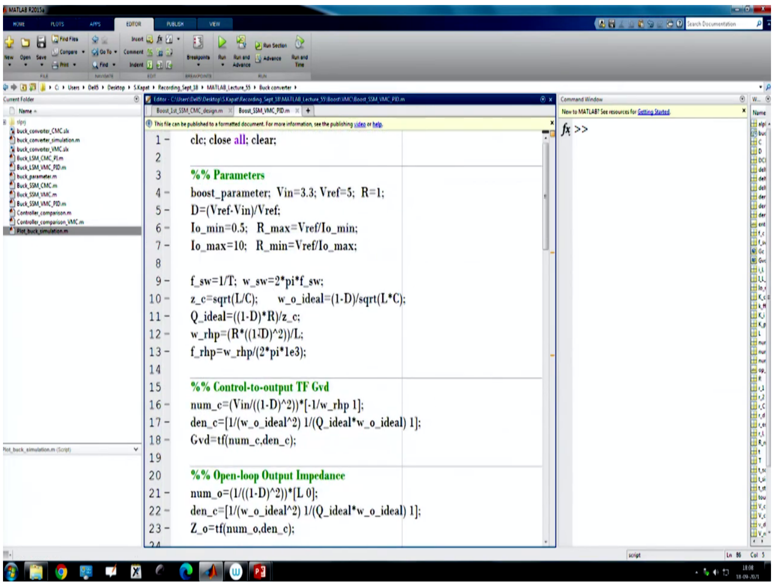

Now, in boost converter first we will consider a voltage mode control technique where we are considering 1 ohm load resistance, 3.3 volt input, 5 volt output.

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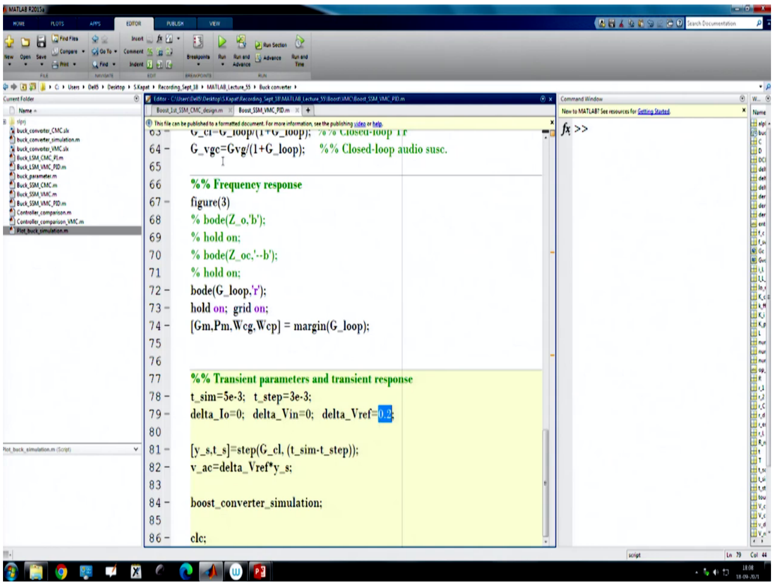

And we are applying a load step transient of you know a reference transient of 0.2 volt ok. So, let us first run it and we will use.

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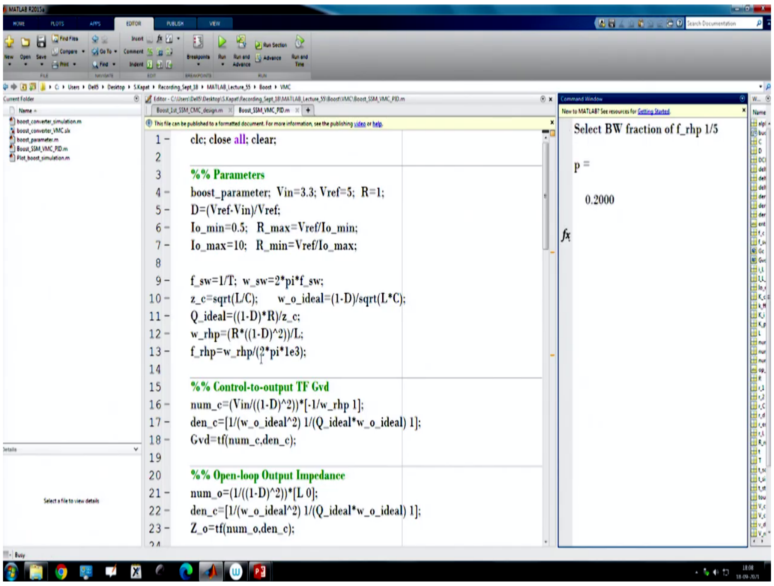

Let us run it. So, it will ask for f rhp and we know for voltage mode we generally go for one fifth of the rhp.

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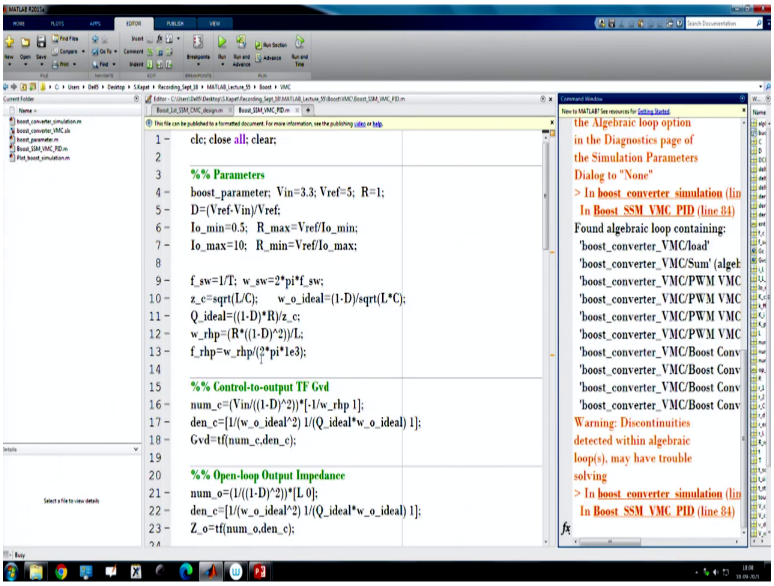

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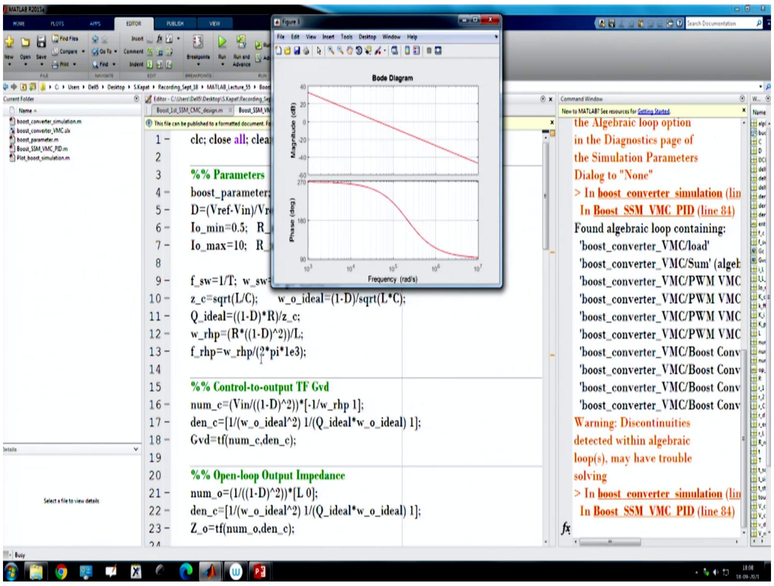

So, let us do that.

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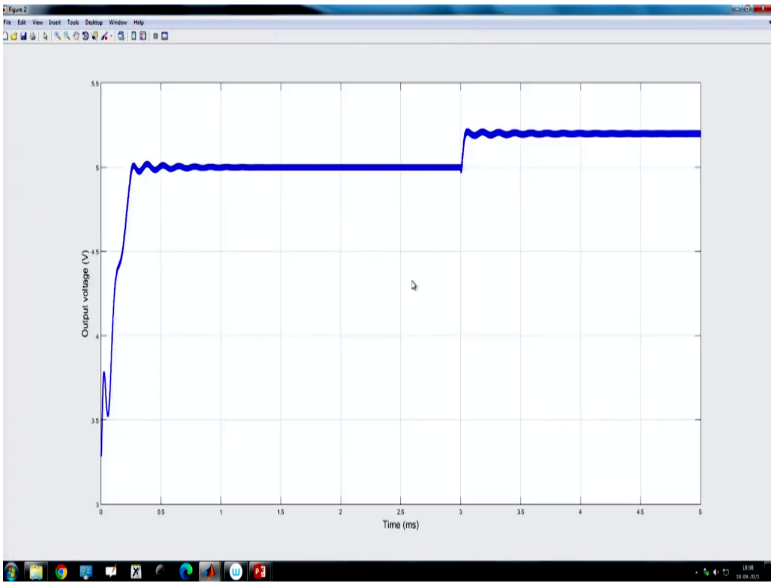

So, this is the one fifth of the rhp. So, this is a blue color.

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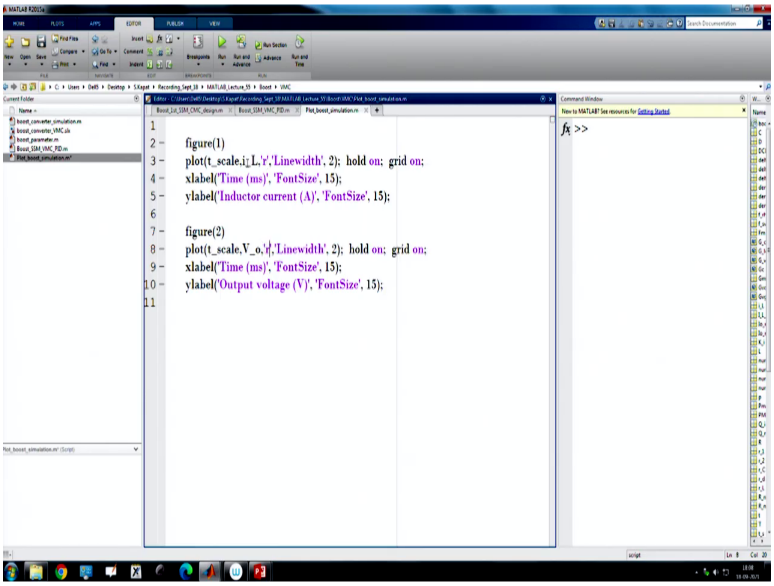

Now, we are using the same red color for current mode control. So, we will go to current mode control we will hold it.

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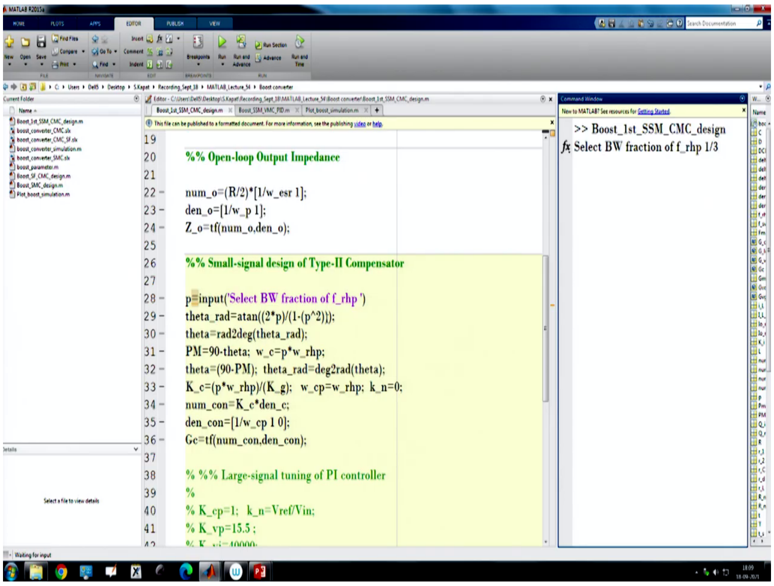

Now, we will go for traditional current mode control where we can go up to one third of the rhp zero. So, one third of the rhp zero we can go right.

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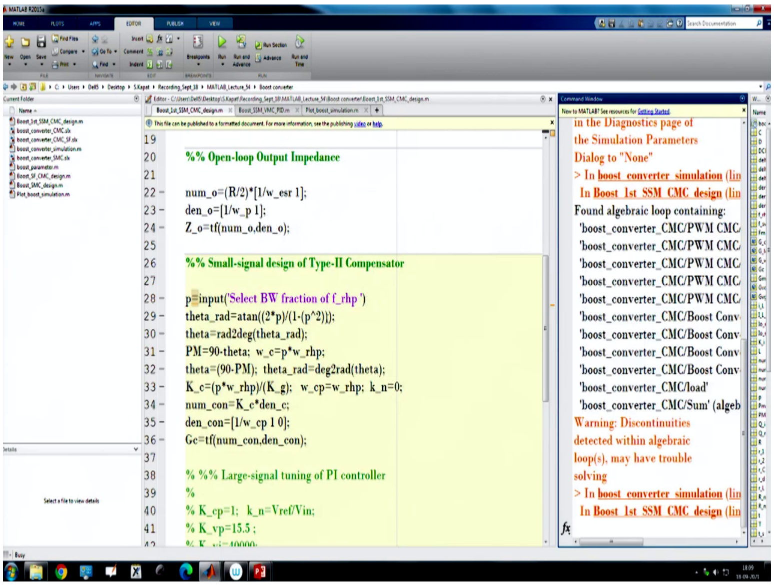

One third of the rhp zero we can go.

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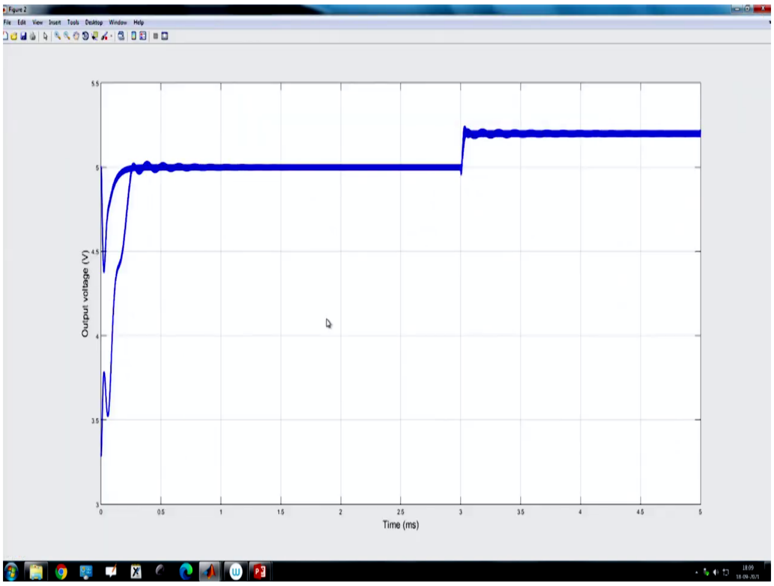

And let us check ok. So, I think we should change the color.

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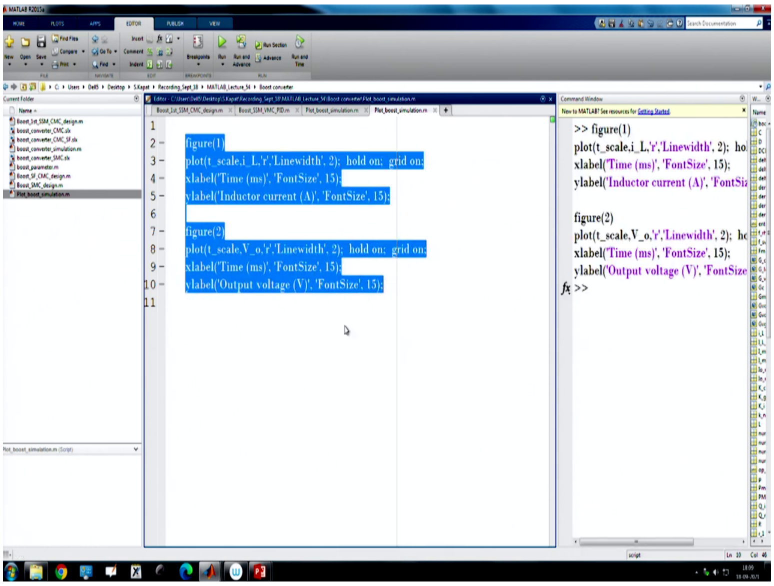

So, we should change the color one third of the rhp zero. Just hold on. We are redrawing this we are ok.

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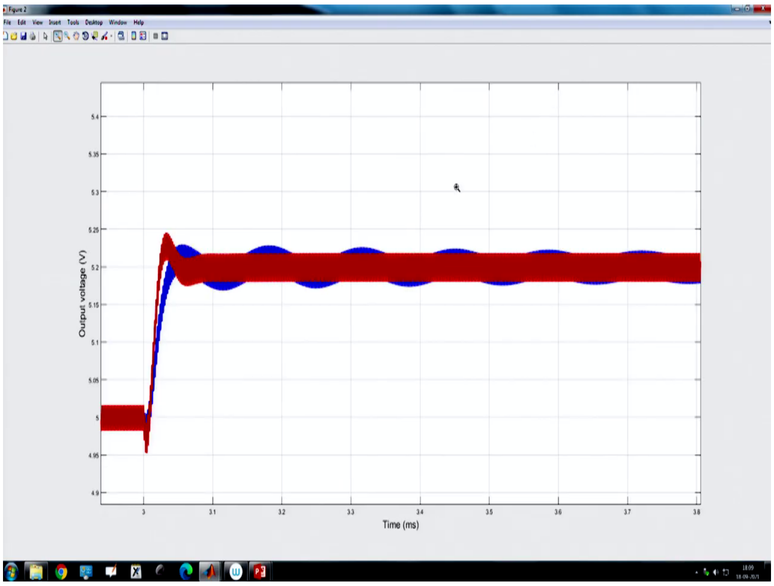

So, we have drawn one for voltage mode control.

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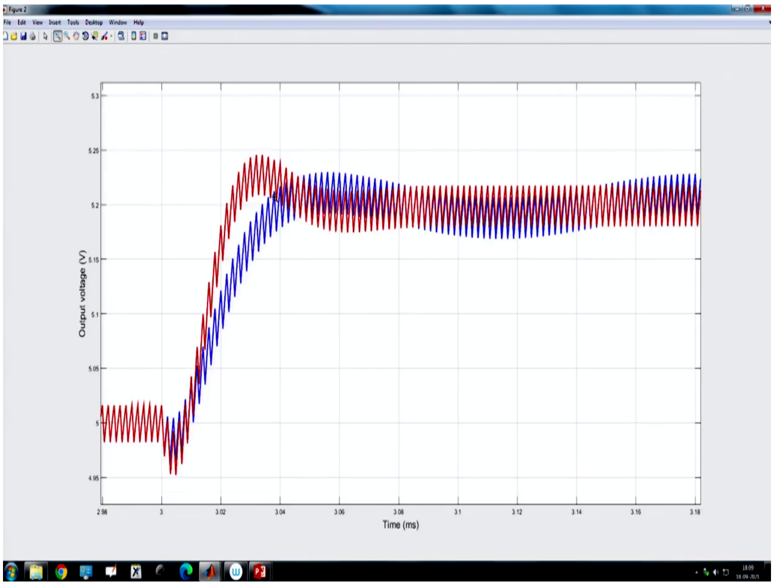

And the other for current mode control.

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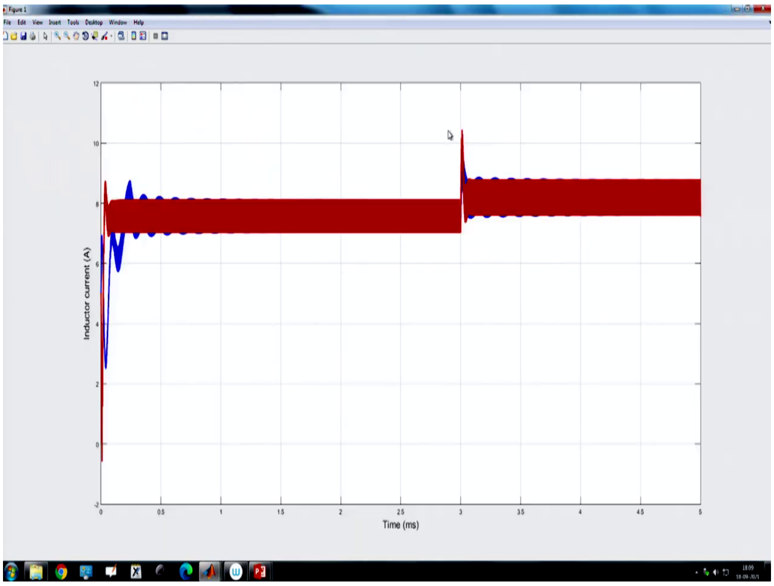

And these two are their inductor current.

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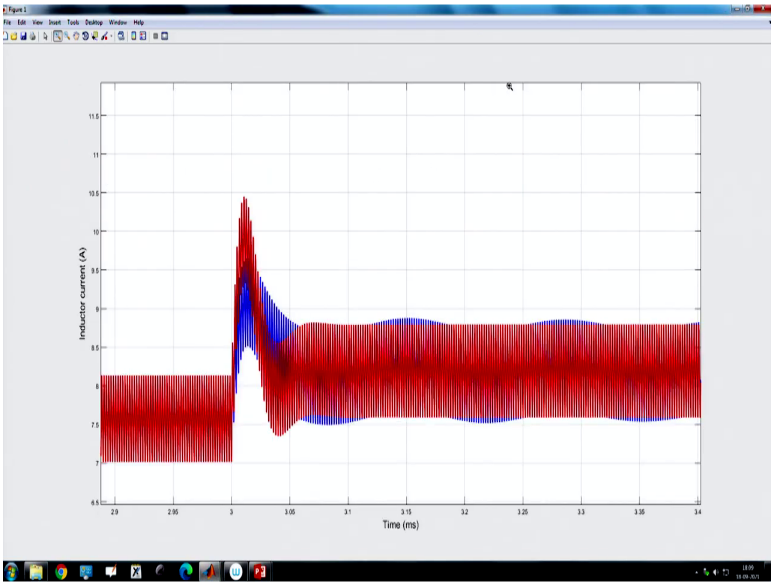

For voltage mode, we took one fifth of the rhp zero.

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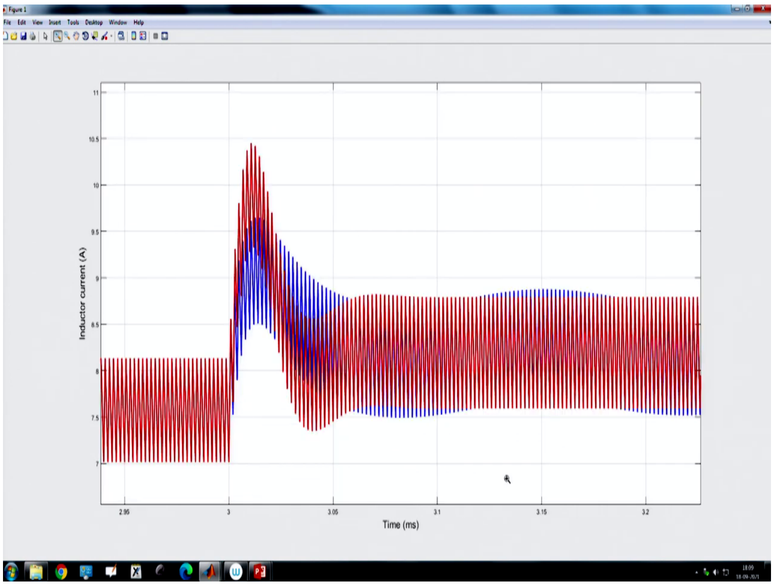

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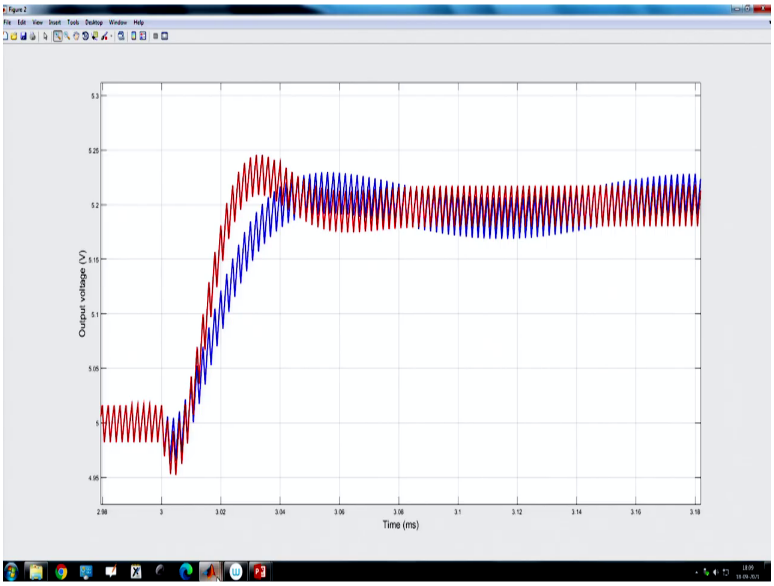

For current mode, we took one third of the rhp zero and it shows a non-minimum phase behaviour. Now, we are going for large-signal based tuning.

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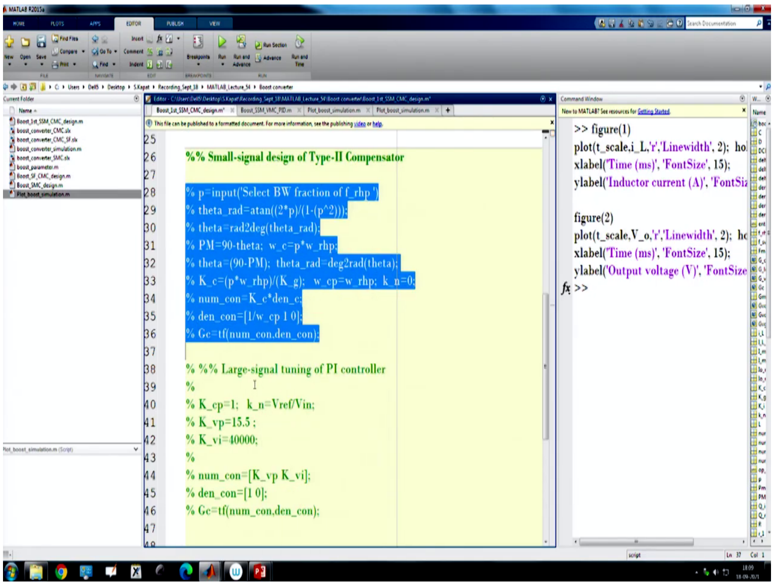

Where we will disable this small-signal tuning comment and we are going for large-signal tuning.

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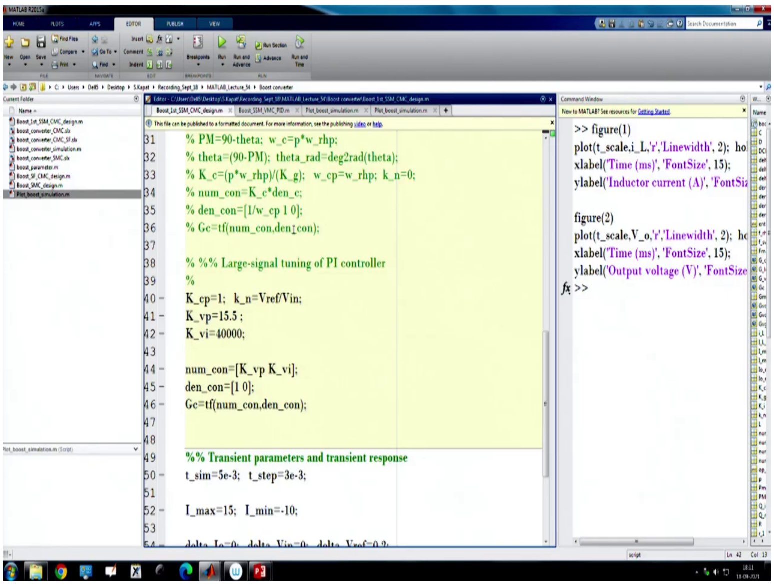

And as I told for large-signal tuning, the voltage can be derived using the expression.

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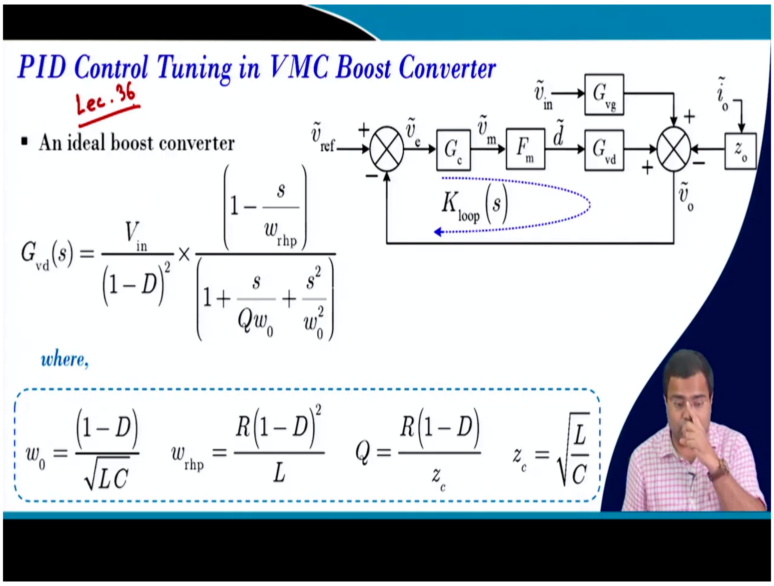

So, if you go for that. So, let us first derive in voltage mode control. We know how to you know how to derive the gains and we have discussed in lecture number I think 36, we have discussed in detail different parameter of the open loop plan.

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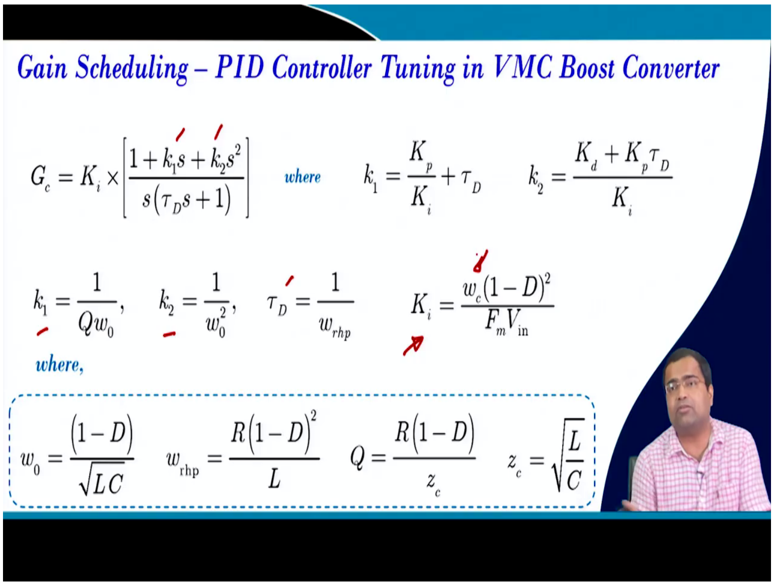

Then for the PID controller design what will be the optimal PID gain, k 1, k 2 these are here k 1, k 2, then tau d is a band limited derivative we are considering, integral gain this will require the crossover frequency and from here we are getting all the controller gain that we have discussed.

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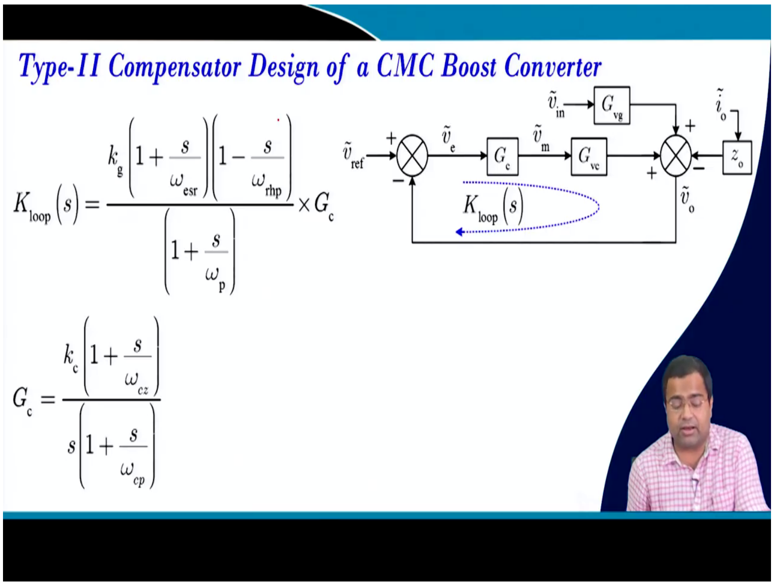

And we know that how to current mode control we have also discussed you know; that means, you know there is esr zero, rhp zero, and we can go to type 2 compensator design.

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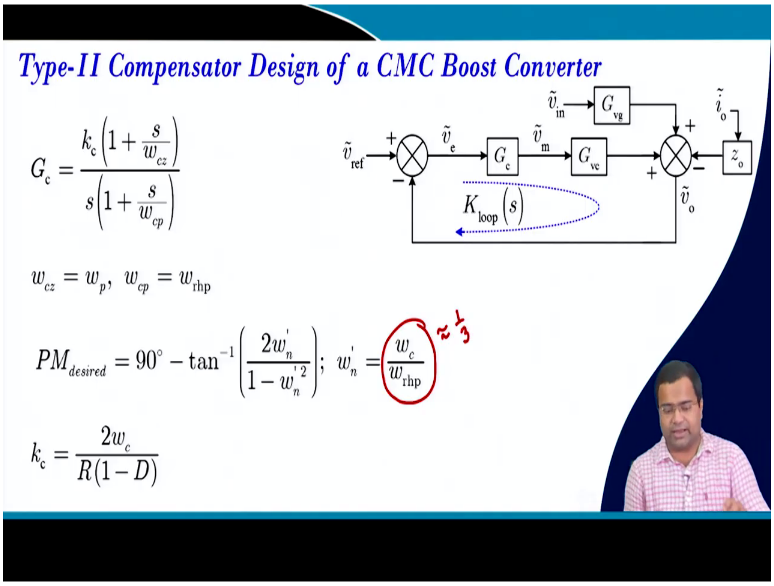

And the design parameter we have also discussed how to set. That means we have to take omega c by omega rhp and that we are taking like a one third; that means we are taking 1 by 3 and this will compute the gain that we have derived.

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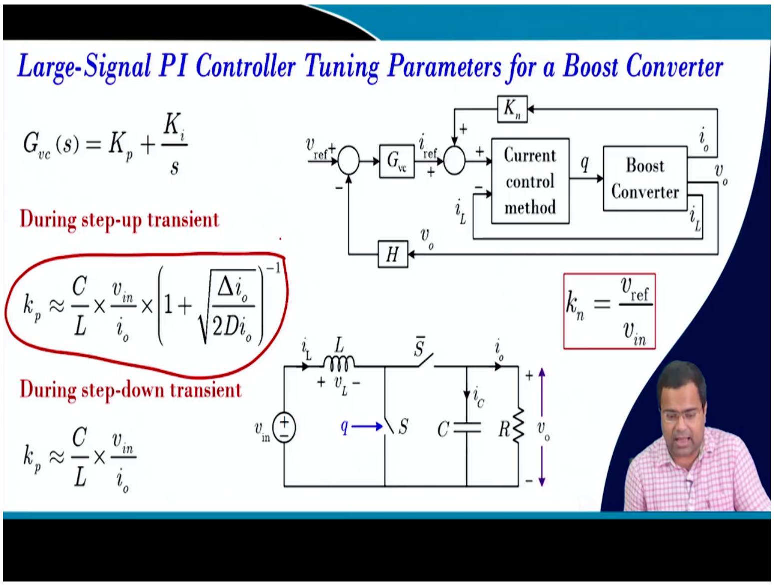

For large-signal tuning, we know the expression and as I told the expression is somewhat you know is not very complex somewhat. So, we have computed this value. This is for load transient we can also do for reference transient. We have computed this value and those values are plugged in into this MATLAB code and we are comparing now we are using a different trace.

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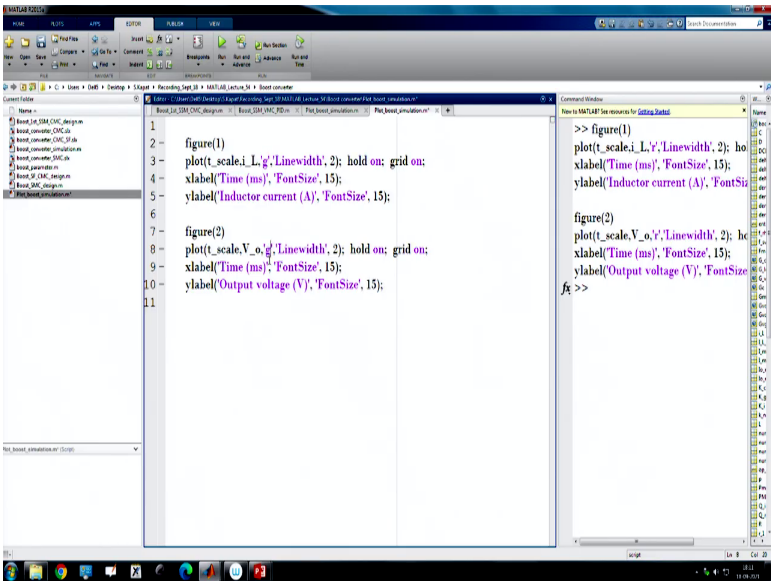

So, we are using green color trace; green color trace.

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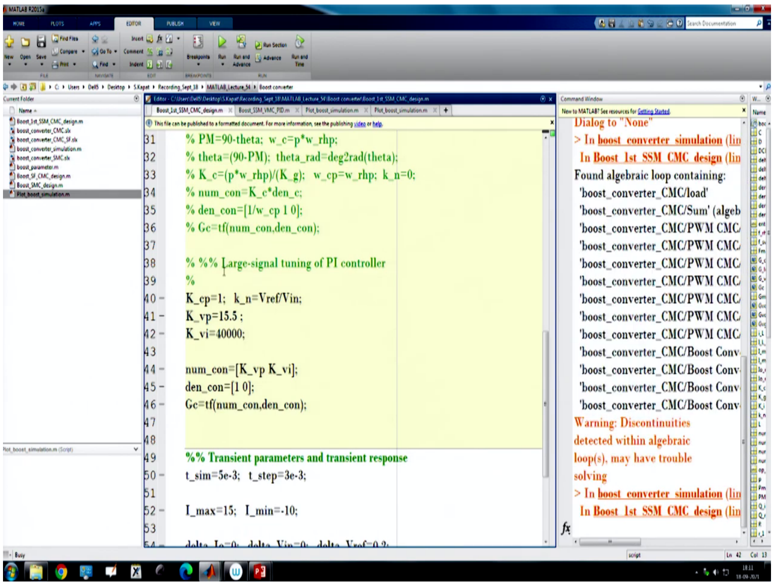

And we are using now our large-signal based tuning.

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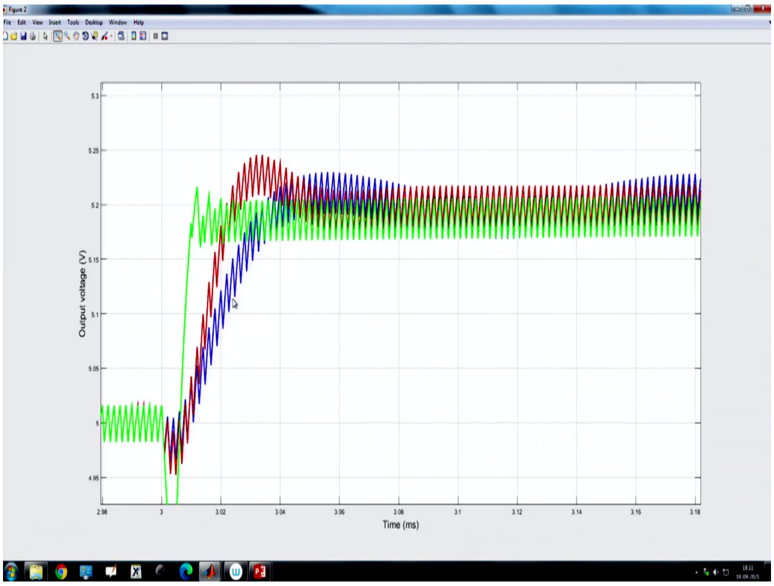

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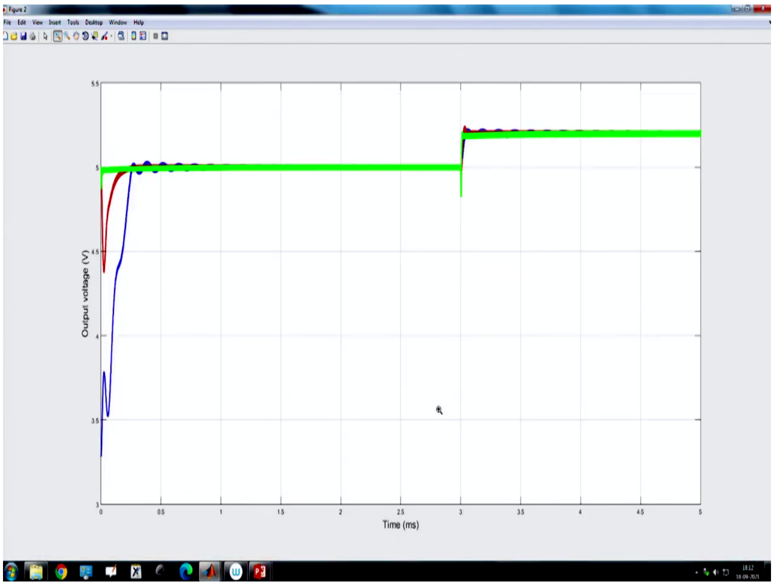

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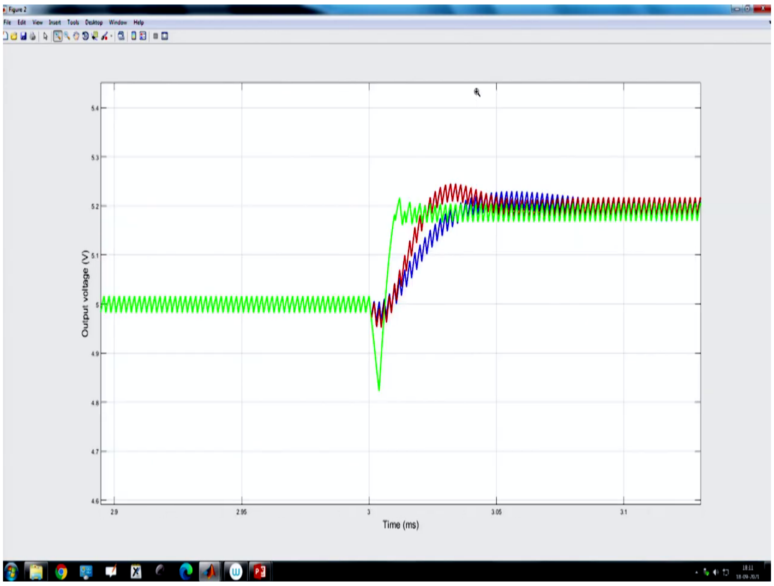

So, in large-signal based tuning you will find.

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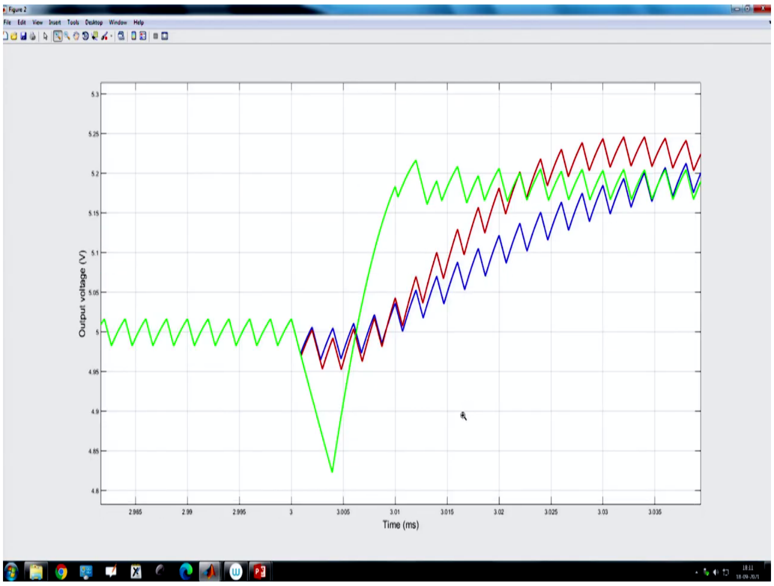

That it is reaching in one cycle, but there is a problem: the response is very fast, but unlike in buck converter where the time optimal control also achieve minimum voltage undershoot, but here the voltage undershoot drastically increases because your on time is large.

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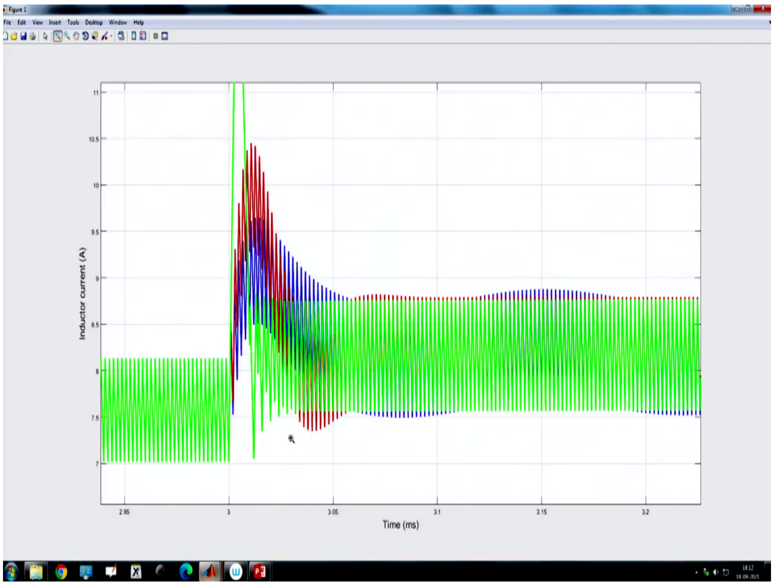

And if you go to the current waveform, you will find.

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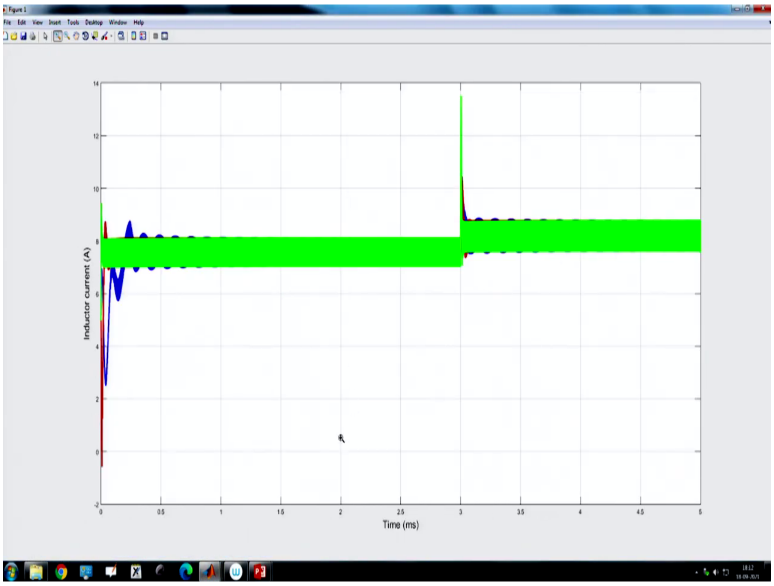

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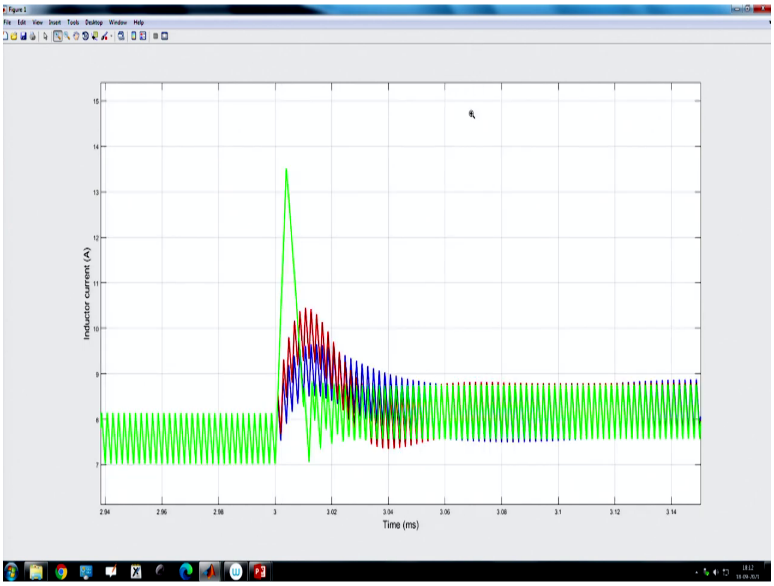

You have a high on state on time.

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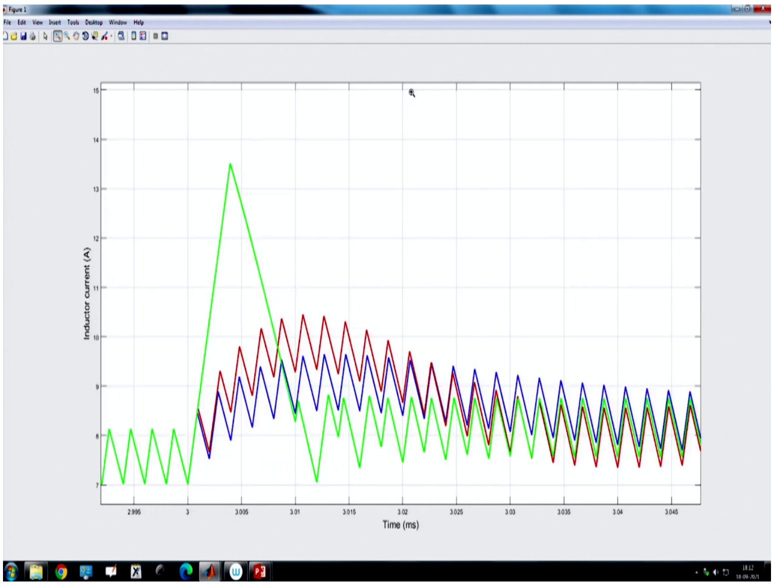

Because the current is increasing and as a result of a longer on time, your voltage will simply fall.

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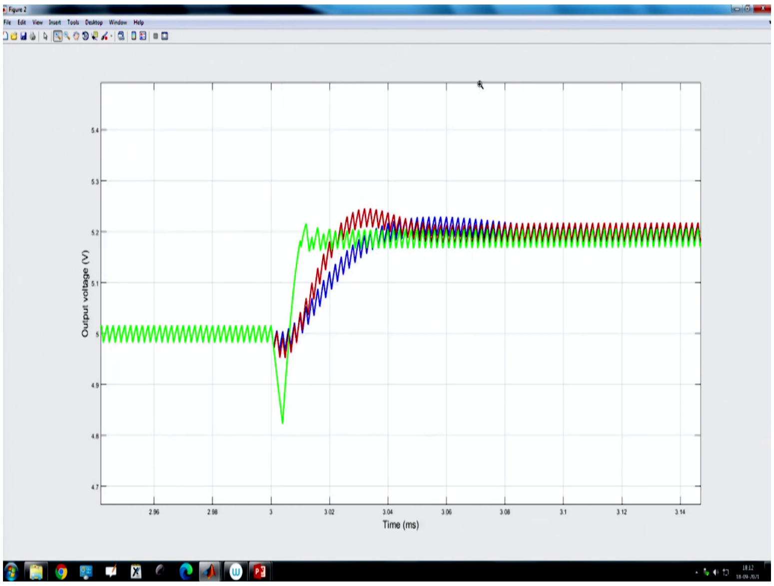

So, while it achieve very fast transient response, you know it is in reaching in five switching cycles.

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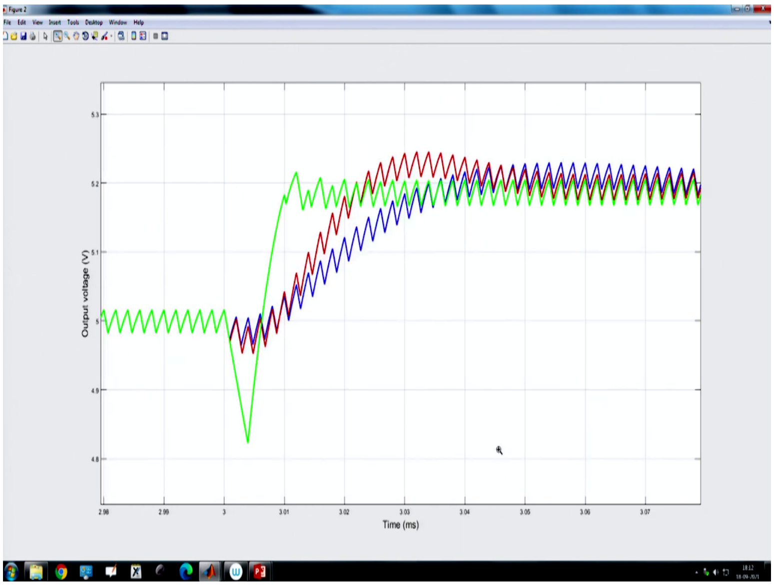

Current mode is faster that voltage mode and current mode, but it comes with this price.

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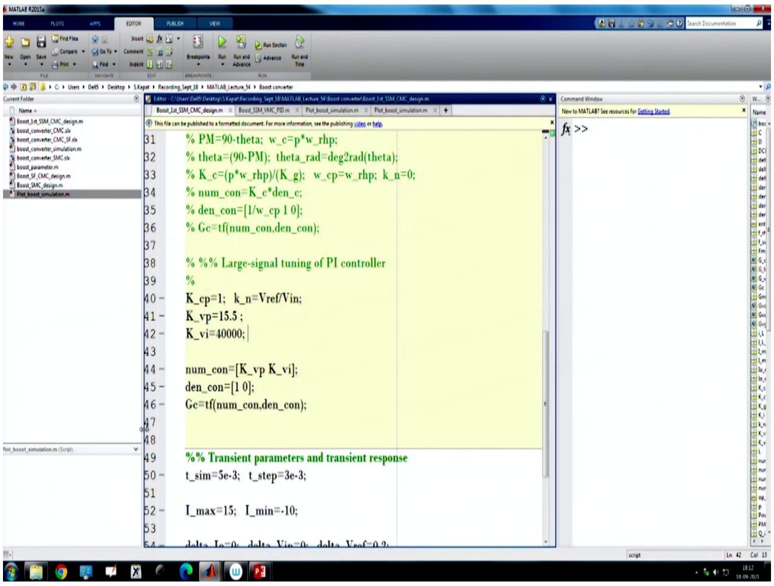

But, we can always set a current difference.

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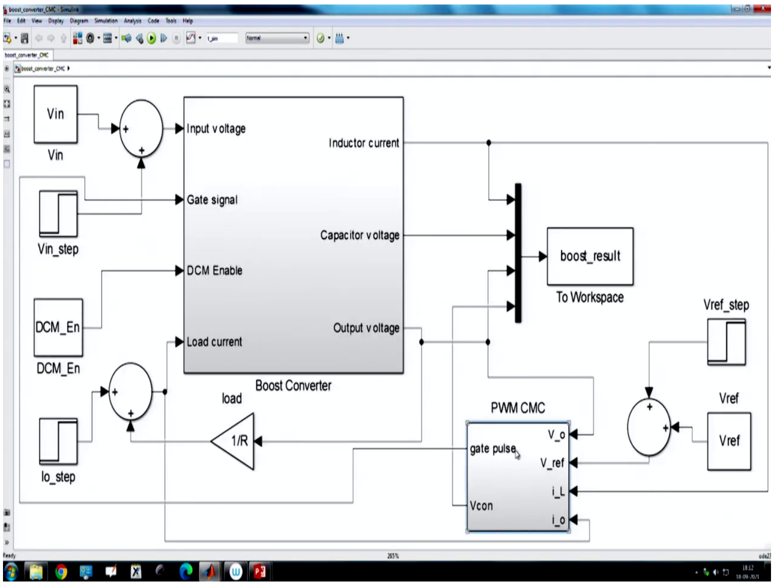

So, if you go to current mode control, you know if you go to our current mode control.

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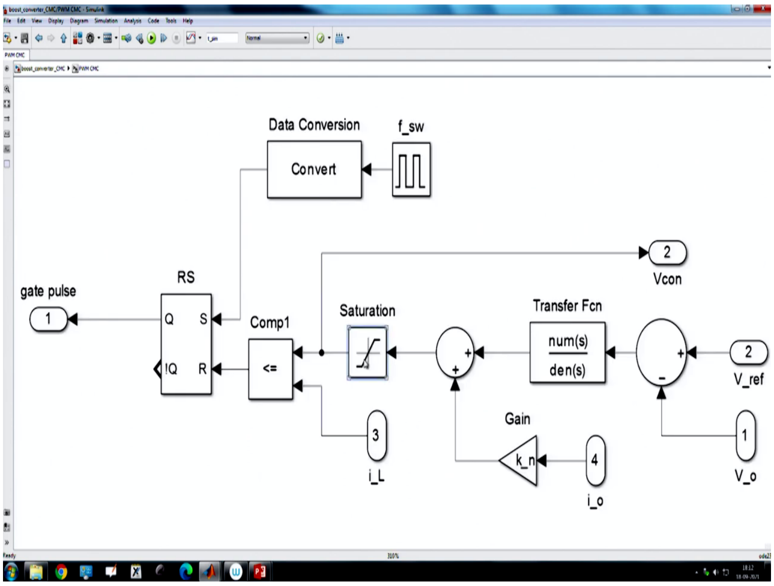

We can always set a current difference.

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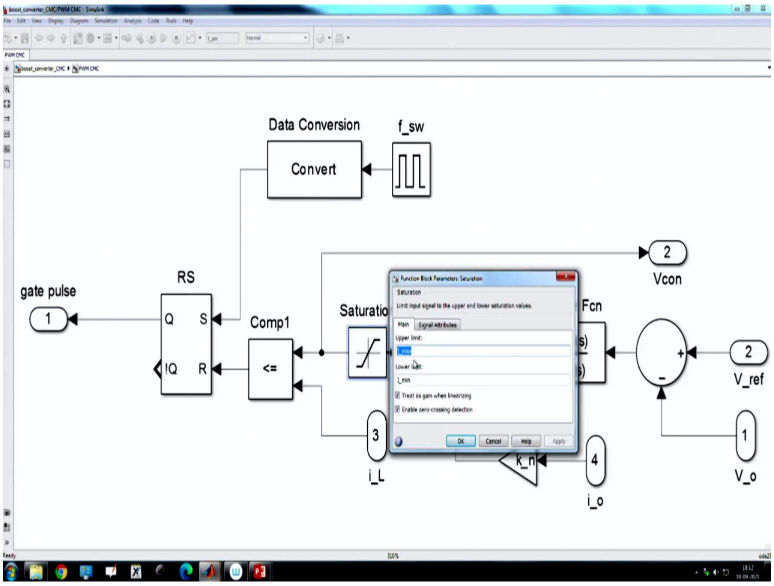

So, this current difference I max that we are setting from the MATLAB file and if you go to the MATLAB file. So, this I max we can reduce this I max value ok.

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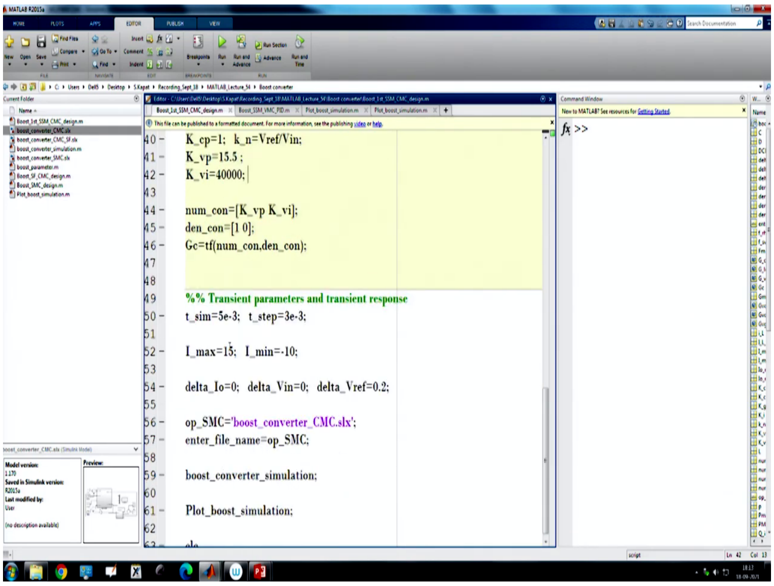

So, let me check I max. So, here it is 15 ampere. Let us say we make it 12 ampere.

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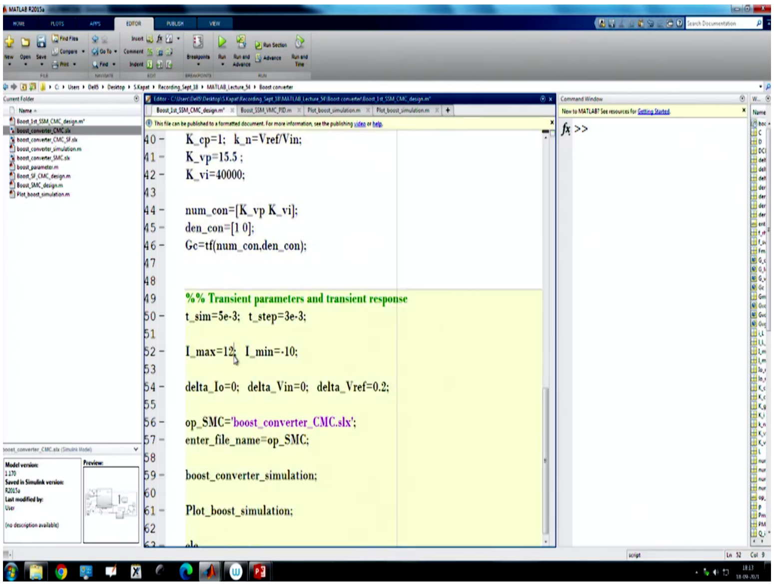

So, we are setting a current limit. We rerun it; we want to rerun it and now we are using black color.

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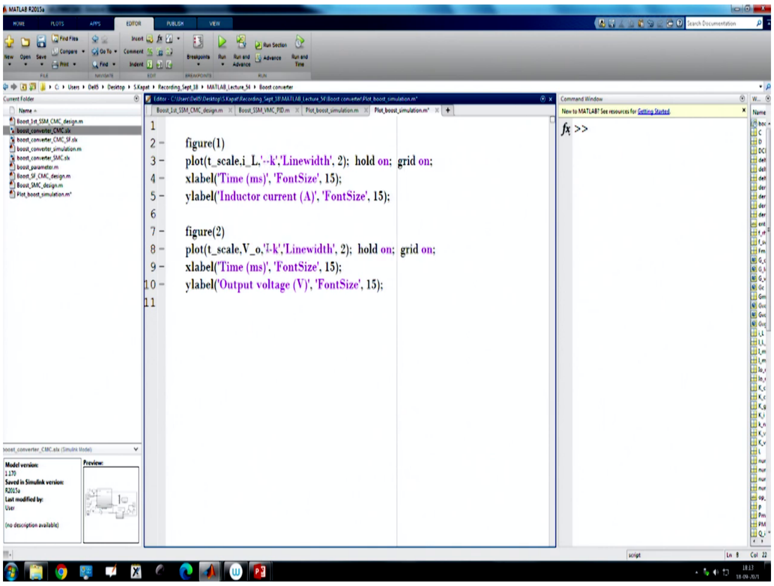

Let us say black dotted color dash color. So, if we want to set a current limit and run it.

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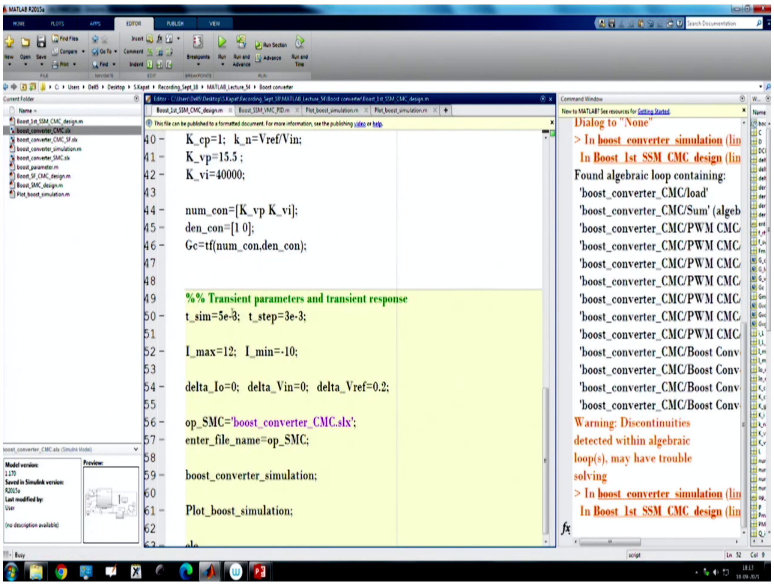

And let us see what happens.

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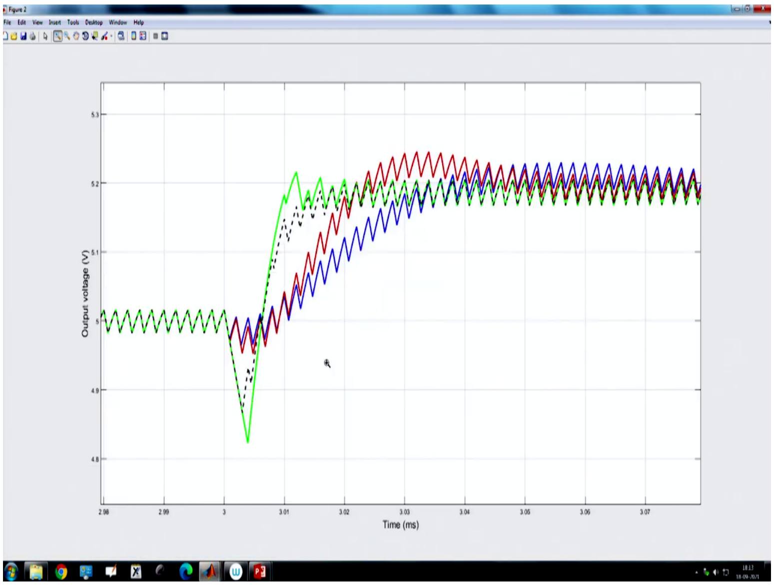

Because now we are putting a current limit.

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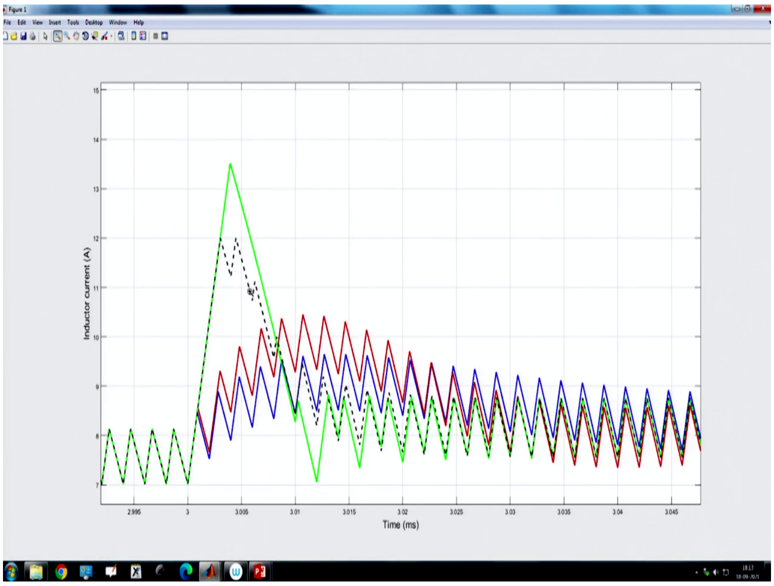

So, once you set a current limit, you see.

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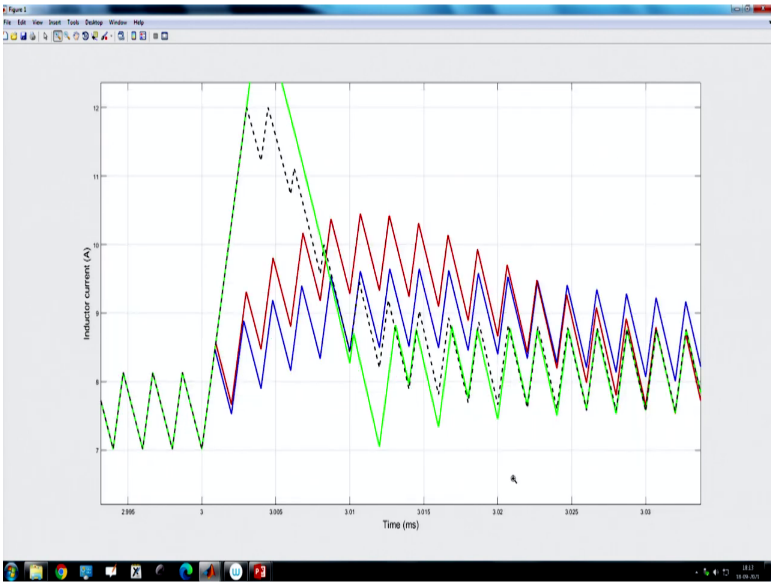

The inductor current is reduced to 12 ampere because we can set according to our current rating.

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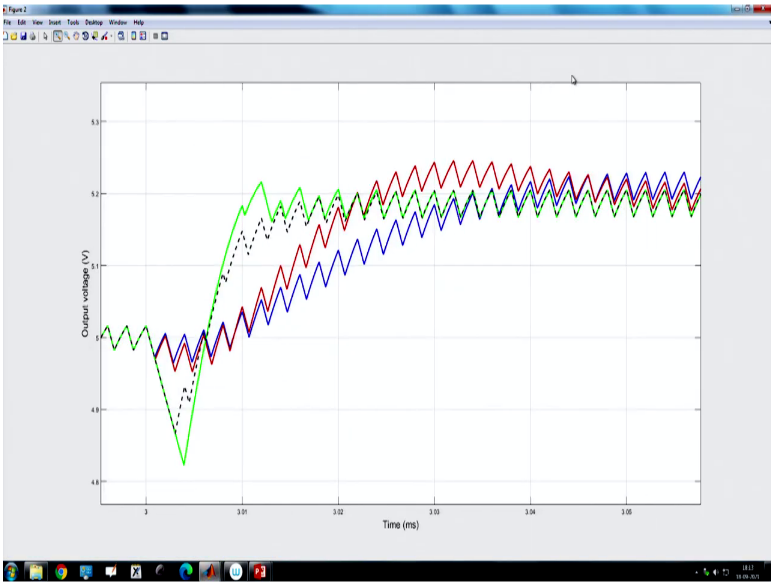

And the response is still much faster than both these control techniques.

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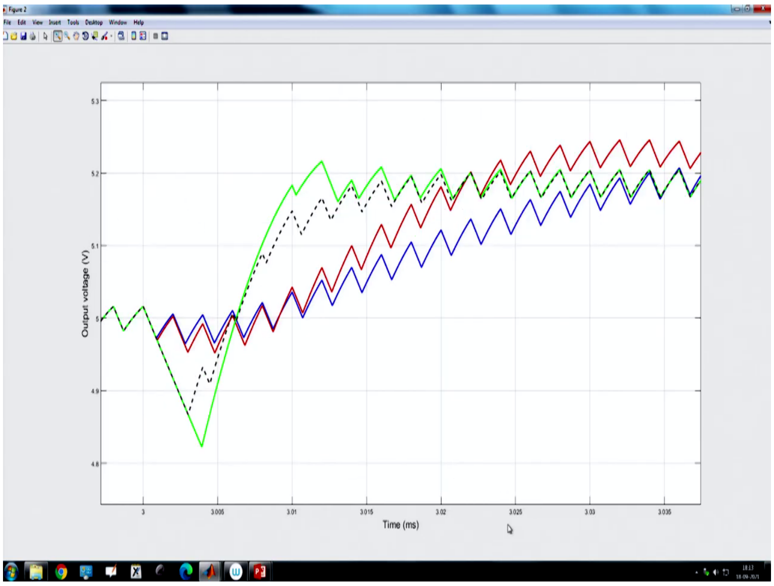

Because it is taking a few more cycles. Earlier it was just taking 5 cycle, but now it is taking you know 10 cycle.

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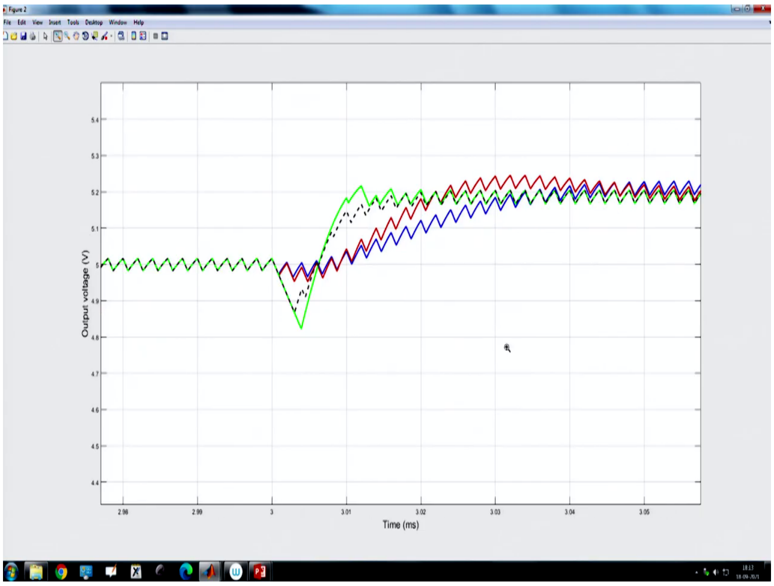

But, it is faster compared to our you know traditional current mode and voltage mode control.

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Because you can see.

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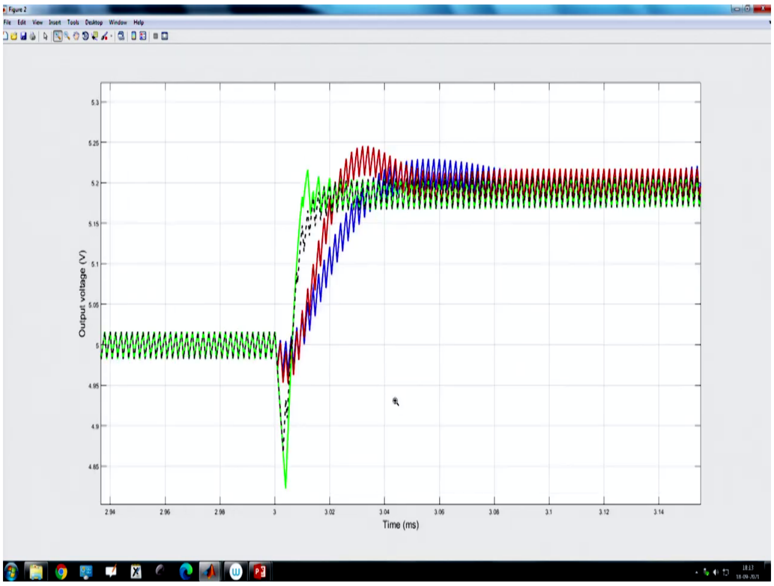

So, this blue one black one is reaching much faster, right?

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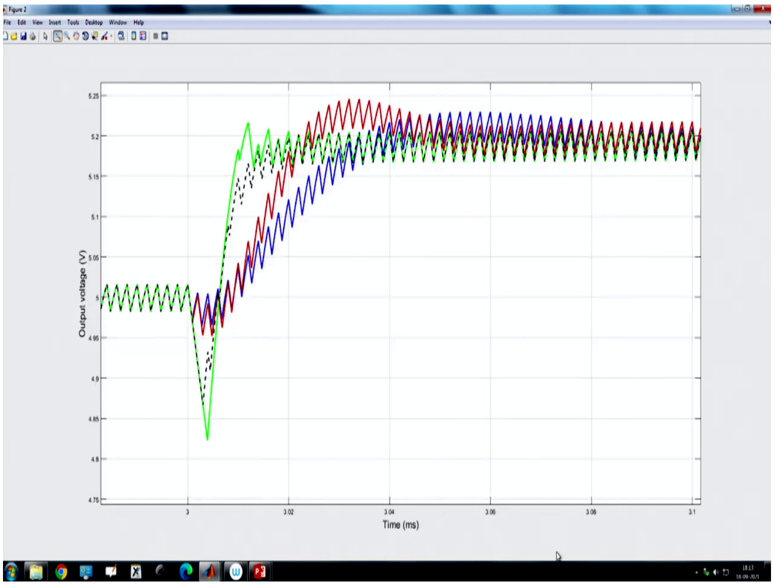

So; that means it is much better than and will show you in the subsequent lecture with the experimental result we have; that means, with optimal tuning using linear control, then with optimal tuning sorry. We have compared the optimal tuning, which is a linear controller tuning. Then we also set our current limit and we want to show that all these responses are much faster than what we can achieve using small-signal based tuning.

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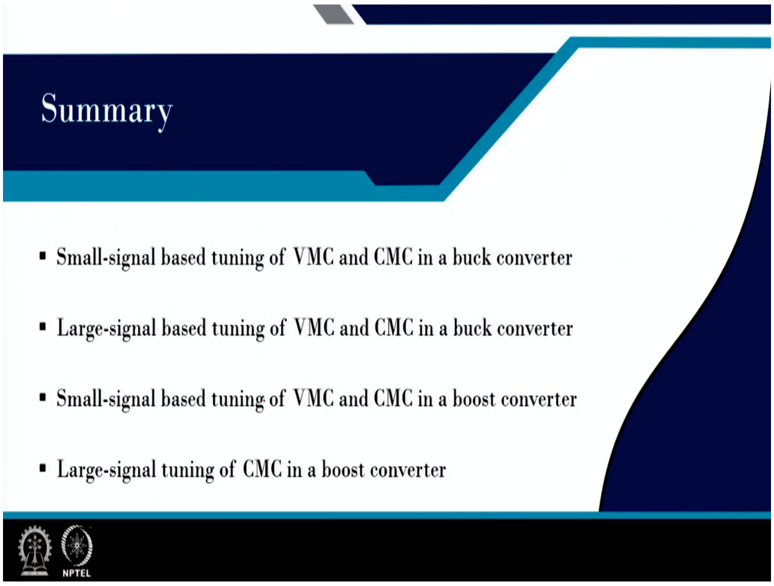

So, in summary, we have discussed small-signal based tuning of voltage mode and current mode control in a buck converter. We have discussed large-signal based tuning of voltage and current mode control of buck converter. We have discussed the large-signal and small-signal; we have discussed small-signal based tuning of voltage mode and current mode control in a boost converter.

And we have compared the large-signal based tuning of current mode control in a boost converter with and without current limit and we saw the large-signal based tuning can significantly improve the transient performance of DC-DC converter compared to small-signal model. So, with this I want to finish it here.

Thank you very much.