Control and Tuning Methods in Switched Mode Power Converters
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Module - 10
Boundary Control for Fast Transient Recovery
Lecture - 47
Boundary Control Techniques and Selection of Switching Surfaces

Welcome. This is lecture number 47. In today's lecture, we are going to talk about Boundary Control Techniques and Selection of Switching Surfaces.

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So, here first we will talk about the switching control law and what are the performance objectives and what are the motivations. Then, we want to visualize trajectory and time domain behavior in switch mode power converter. Then, we talk about selection of switching surface like we will talk about first-order surface, then higher-order surface and then, we want to discuss some switching surface like a trade off like a performance, complexity, cost trade off. And here, for first order switching surface also, we are going to consider few MATLAB case studies.

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So, first we have to make our motivation clear. So, if you take a DC-DC converter or switch mode power converter. Here, I have taken a buck converter example, but you can take boost converter or any other hard switch converter. So, the first objective we need to achieve very fast transient response and this transient can appear you know this transient. So, there can be load transient, there can be reference transient and there can be supply transient.

We are primarily interested in this load transient, is very critical, because if we are talking about low voltage high current application where the there can be frequent load transient and the step size can be quite large. If you consider you know reference voltage transient and there are many application like a dynamic voltage scaling application; even if we talk about the DC bus voltage DC link voltage, you know if you want to change then, the DC link voltage it may be the output of one converter.

So, we need to change. We need to change the reference voltage; that means, if we talk about a cascaded converter like a for constant power load like for 40 to 1 volt application where you know there is an intermediate bus converter which can be a normal buck converter or it can be an isolated converter and then, followed by a multiphase converter.

So, in the first stage converter, when you want to optimize the DC link voltage, then you need a reference transient for the first stage converter. Similarly, for the load stage, if we want to change the VDD of the digital processor then, we need to do supply reference transient for the second stage. So, this is also very critical.

And the supply transient also is very important, because we need to reject the disturbance in the supply. So, that output voltage should not be affected by the change in input voltage; that is one of the objective. Now, the load transient and reference transient. Particularly, load transient can happen frequently very frequently. In fact, you know in industry; we design a power converter or PMIC power management IC; let us say for VR (voltage regulator) applications.

So, if the switching frequency of the converter is 1 megahertz so, they can test the load transient in some orders of you know 10s of kilohertz and even up to 100 of kilohertz even for feasibility. Whether the converter will sustain or not, they can even go very close to the switching frequency just to check whether or not the converter survives.

But the converter cannot respond beyond a certain frequency of the load transient and control will play a significant role that how fast load transient we can cope up using the converter; that means, only by increasing switching frequency may not be the only solution. So, here, control can play a significant role and that is what we are going to you know explore; what are the fastest transient technique that can be applied for a given switching frequency or a given converter.

Now, there can be simultaneous that means, the load transient can happen much frequently more frequently. In dynamic voltage application, the reference voltage and the load can go together change in, because you know we are talking about a devious enable system, where we need to optimize the dynamic power.

So, when suddenly one task requires a sub certain voltage level. So, we need to change the voltage. Suppose, if the voltage requirement is high; that means, the task is more intensive and we need to finish within a deadline. So; that means, the load is already high and as well as; we need to increase the reference volt so, there can be simultaneous step transient.

And at the same time, we need a very high energy efficiency, because we generally consider efficiency at steady state, but those are steady state efficiency. But if converter undergoes very frequent transient then, steady state efficiency is not sufficient. Because if we can optimize the transient performance, we can save the driver loss and other stuff so that we can also achieve high energy efficiency for a longer duration over a time period.

The implementation simplicity that means, our switching control law should be simple to implement, because we will target for high frequency application and also we have to, because the motivation another motivation is that we are trying to explore the switching control law which can be applied in commercial product and this can be used for very high frequency application.

So, that is why the control logic should be simple. It should not take much resources out of them, because ultimately it comes in terms of price. So, if the control logic is complex then, it may require more transistors or resources for the IC level and that will increase the silicon area and that will increase the cost. So, the complexity will come in terms of price and also, in terms of power consumption. So, we need to make the design simple implementation simple.

Another important. Since we are talking about the switching control law and we are going to visualize from the large signal point of view. So, we need to ensure that the system should be stable, not in terms of. You know there are different type of stability. And you know we talk about small signal stability that we discuss. When we consider the transfer function base approach where we talk about gain margin, phase margin and so on, but here we are not talking about small signal. So, in this context, we are not talking about small signal.

There are two more stabilities a large signal stability; that means, the system should not collapse, and this is very important particularly for boost as well as a non you know I will say the indirect power converter transfer power transfer converter, where initially we take the energy in the inductor and then you transfer to the output side.

So, if we do not take a proper care, it may so happen; if the large-signal it is unstable, the whole system can collapse and it can burn like you know the inductor can saturate and it can damage your devices as well. So, you have to be very careful. And we also talked about fast-scale stability; that means, at steady state, we should not end up with sub harmonic oscillation. So, because that will increase the ripple parameter that will degrade efficiency and that will also degrade the power spectrum, because it will make a design of you know the input filter very complex.

So, we need to keep these of the motivation. And finally, our analysis of what we are doing with phase plane should be very simple so that we can visualize that how trajectory moves. How can you link this trajectory to our control law as well as can we link some of this

switching logic with our conventional PID controller? We traditionally use and which very much well known? So, these are the objective into the lecture.

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So, we will start with the boundary control for time optimal recovery ok. So, what is that? Let us consider a buck converter. Here, our q is the controllable gate signal. Again, we are assuming ideal one, but you can always consider the dead time practical parasitic and that we have discussed earlier.

But here, we are trying to build the concept fast. So, the objective here; we need to turn on and off this controllable switch, because the other switch ideally is the complement of this high side switch, but practically there will be dead time. So, our objective to generate this on time and off time of this control S; the controllable switch, which is the high side switch for a buck converter and it is the low side switch for a boost converter, because that switch you are going to control.

So, we need to generate a set of on time and off time. What are the objective? And this was initially investigated fast that how can we synthesize this set of on-off trajectory set that set of on-off time using the trajectory information, which will result in time optimal recovery. So, the objective is to find the set of timing parameter to achieve fastest transient recovery. And it turns out to be that it is simply a bang-bang control on-off control and it you can achieve the fastest recovery by one switching action.

And that was first reported in that Wilson and Burn that you know in that paper Burns and Wilson, initially they have investigated.

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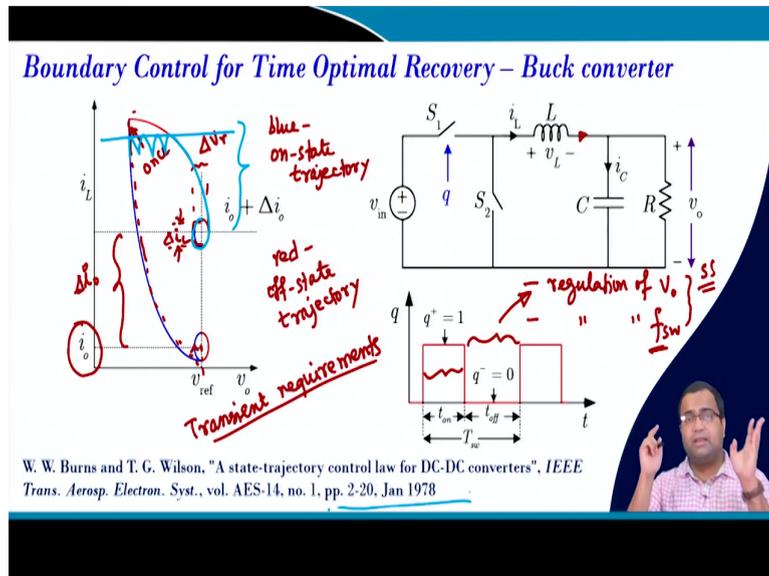
And it turns out to be if we take. Let us say buck converter and we will soon see how can we visualize this phase plan behavior into time domain behavior. So, here the blue line indicate the on-state trajectory. So, I would say the blue one indicate on-state trajectory on-state trajectory and the red one indicate off step off-state trajectory ok.

So, now, the objective. Suppose, initially, it was you know with the load current i 0 that was our initial load current. Now, suddenly there is a load step transient with the step size of here. It is delta i 0 is the step size; that it undergoes a load transient with the step size of delta i 0.

Now, the question is when it was in a steady state, you can find that the on-state trajectory is on for certain duration t on and the off-state trajectory is activated for the duration of t off. So, we need to choose this on and off duration under steady state in such a way so, it meet the regulatory requirement, because you can see in the x axis, we have taken the output voltage and the y axis, we have taken inductor current.

So, for the, because we know for a buck converter, the average inductor current of a synchronous buck converter is nothing but the load current. So, for a given load demand, we need to ensure that the average value is v ref; that means, that is my desired reference

voltage. So, we need to set a set of on off time, which ensures the voltage regulation at v ref in the average sense, which should achieve certain desired time period.

Regulation of output voltage. The second one is a regulation of switching frequency whether is it possible always to regulate or not; that we are going to see. But these two are sort of steady state requirement that means, if you make it, it will ensure that steady state, but apart from that. So, this is like a steady state requirement, but we also have a certain objective in the transient requirement; that means, certain transient requirement.

So, what are the transient requirement? What should be our on-time for which the on-state trajectory will be activated and my off-time; such that it will only change its state once, it will only change its state once; that means, this is like a one switching action. So, first it will turn on for this duration and then it will turn off and eventually, in one switching action, it will come to the next operating point. And here, this particular width is nothing but our current ripple, our current ripple. And this particular width if we take, is nothing but our voltage ripple.

So; that means, again in one switching action, it will come to a steady state with its desired current ripple and desired voltage ripple. So, the desired current ripple, and the desired voltage ripple will be determined by the switching frequency or the values of the on-off time and their ratio will decide your regulation; that means, where we are going to regulate.

But during transient we are not going to talk about regulation, because we need to choose the right on-off time such that the trajectory after one switching action, it will come back. So, the question is it will be very difficult, if we try to do by timing base control; that means, exact calculation of the time.

The only thing this concept is proved well proved that one switching action will lead to time optimal recovery, but if we have more switching action, then definitely you may not, you will actually deviate from the optimality condition. So, then it is under certain constraint. That means, suppose you know here, one of the problem is that you will have a current limit.

Suppose there is a current limit, then what you can turn on here and it will go like multiple switching action. Finally, it comes back here. That part we will discuss in the subsequent lecture under a constraint on the current limit, because this you can see there is a high current overshoot.

So, this is my current overshoot. Sometime, this current overshoot may not be acceptable, because there can be some limits in the inductor. But in generally this current limits are ok, but even if you put a limit and we have to device a control strategy, where it will not allow the inductor current to go beyond a certain value. There should be some kind of current mechanism under current control mechanism.

Similarly, under the limit, what could be the performance and how it will deviate from the optimality performance. But it is clear if there is no constraint, then one switching action will lead to fastest recovery, which is called time optimal recovery and that was reported you know in 1978.

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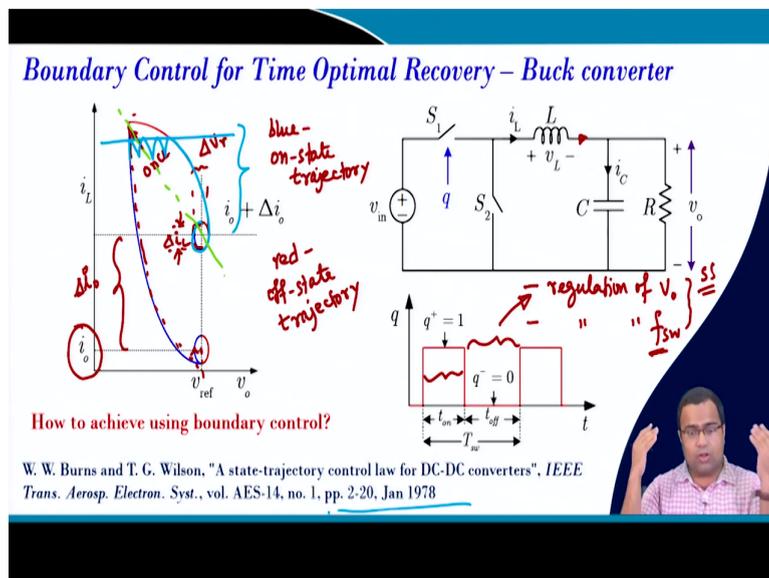
Now, how to achieve the boundary control. So, using boundary control; that means, now the objective is that we need to you know we need to think of some kind of switching boundary, because we have discussed in sliding mode control. So, we need to think of some switching surface and what should be the surface, what should be the switching, you know parameters; that means, you know we know that switching function like a sigma is a function of state and then there will be some parameters. So, what should be the choice of parameter? What is the control law. So, all these we are going to explore.
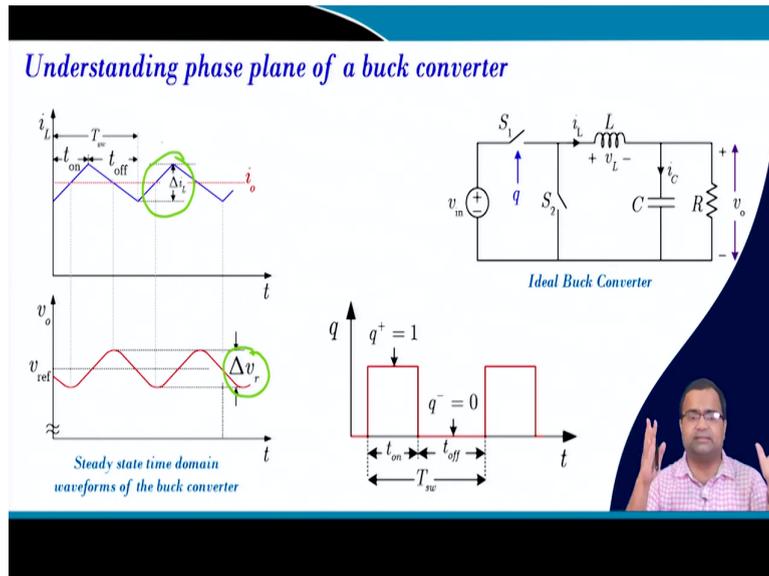
So, understanding phase plane behavior. So, last you know in the last slide, we talked about phase plane behavior, but I told you that we need to choose certain on-off time. So, that you can meet the steady state ripple voltage and the steady state current ripple requirement. So, that is our steady state requirement which will, because this is important in order to ensure that my EMI or my spaw spectrum is set in certain discrete frequency so that I can design the input filter properly.

Similarly, the ripple should be within the specified limit so that you know, because that will decide the power stage design, the capacitor design, inductor design and so on.

So, this is a time domain behavior. And how can we relate this time domain behavior into phase plane. So, if you draw the output voltage in the x axis and inductor current in the y axis.

Then, you will see that this is the one which I have shown earlier; that means, this is under steady state. This is my on-state trajectory ok. So, I can use red color on state trajectory is this, and this is my off-state trajectory ok and as I said if you take this is my phase plane this is my phase plane this is the phase plane behavior this one and if we extend this, then this is a

current in time axis. This is my time axis this ripple is corresponds to this tipple. Similarly, if you expand in this direction.

So, this is my voltage axis, and this is my time axis ok. So, you will set you know this is my current ripple how it is going ok. So, depending upon trajectory. So, you can visualize the phase plan behavior in time domain and it will look like this. So, phase plane to time domain relation in a buck converter current ripple and voltage ripple.

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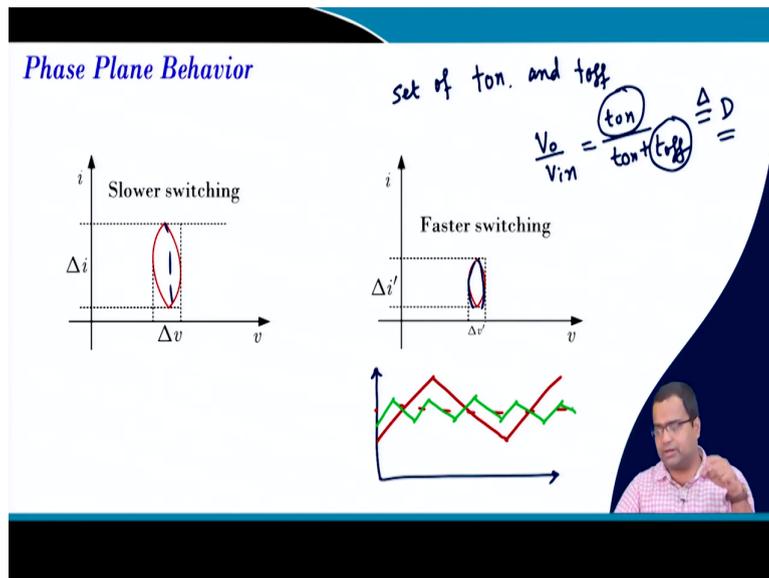
Now, if we as I said. So, we need to generate a set of t on and t off. For an ideal buck converter, your output voltage v 0 by v in we know that it is the on-time by total time on plus off. Now, this, because we are not talking about the practical parasitic and we already discussed that this is something like an equivalent to duty ratio right.

And we have discussed this ideal duty ratio make sense when you are talking about ideal converter, but in reality, the converters are practical and we also know the practical duty ratio is a function of load resistance then DCR equivalent resistance which consist of DCR plus the RDS on that we have already discussed.

But if we talk about an ideal converter; the duty ratio is nothing but the ratio of the on time by the total time. Now, you can have you can reduce this on time similar you have to reduce the off time so that the ratio remains same, because that will decide my regulation point. If we

reduce that then, we can reduce this ripple as a result consequently. So, in time domain, it will look like this.

So, suppose we are talking about in one scenario like current ripple like this and this has an average value of this. And in the other scenario, we are talking about something like this, something like this. So, the average will remain same, but we have increased the switching frequency ripple has come down. So, these are the faster and slower switching.

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Now, we want to recapitulate a sliding mode control concept in a buck converter. So, what we did in the sliding mode control initially. You know if you go to our lecture number 18 46 we will find. The first state variable is the; that means, a previous lecture was voltage error. So, we can take v ref minus v 0 or v 0 v 0 minus v ref. So, I have taken x 1 to v 0 minus v ref and x 2 is the derivative of the error voltage.
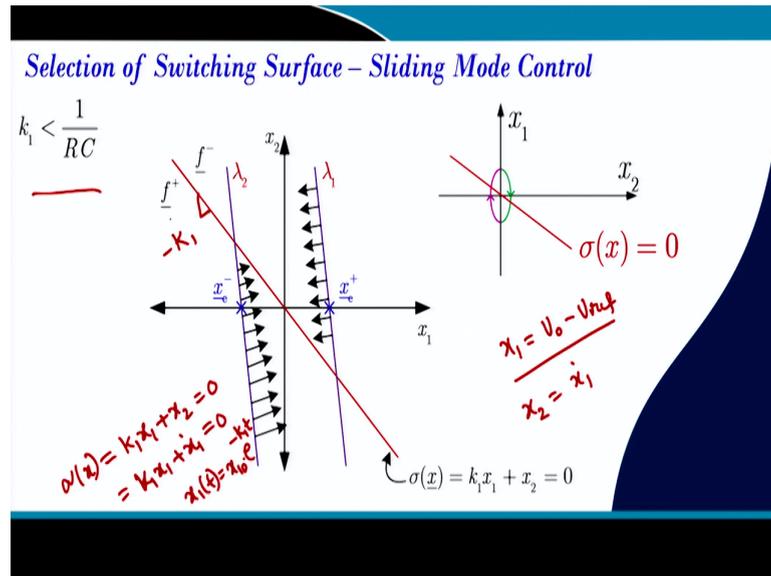
So, now we are talking about selection of switching surface in sliding mode control that we have discussed. So, this sliding surface, we have considered. What is the state that we have considered?. We have considered x 1 to be x 1 to be v 0 minus v ref right. And what is x 2? It is nothing, but x 1 dot; that means, in the sliding motion where sigma x we know we have taken k 1 x 1 plus x 2 equal to 0. Since x 1 equal x 2 equal to x 1 dot. It will be k 1 x 1 plus x 1 dot equal to 0.

So, from here, we can find out x 1 equal to x 1 0 into e to the power minus k 1 t and where k 1 is positive. And here, it is minus k 1 the slope. And we have discussed for different value of slope, the slope can be higher or slope can be smaller. Here, it is a smaller slope. The smaller slope will result in overdamped system and we have already discussed in the context of sliding mode control that you know the sliding motion or you know if we have also discussed the boundary control concept that we are going to take.

So, it will be like you know reflective region; that means, both side the trajectory will be towards the switching surface. So, it will you know have kind of over damped response for smaller k.

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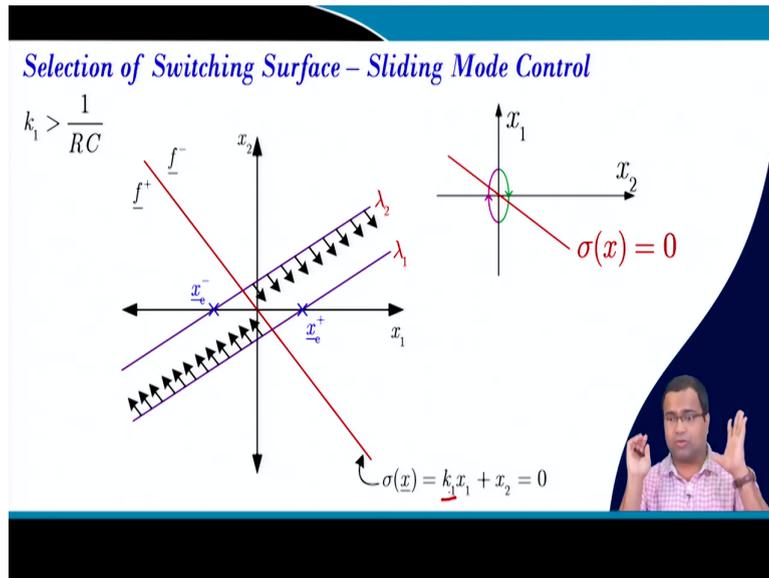
If we increase the k, then we have also seen that this will lead to some overshoot undershoot and then sliding motion ok. So, now our question will be how to select this k 1; that is one of the question and by selecting k 1, can we achieve something close to the time optimal or not.

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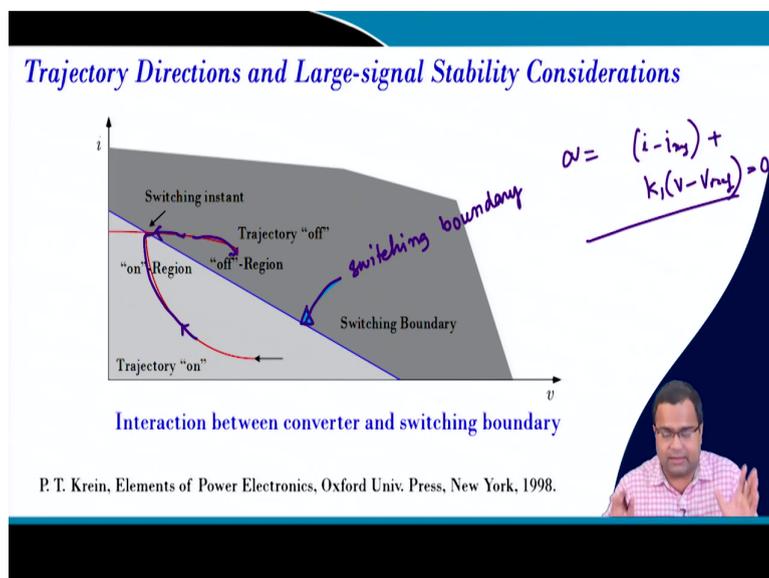
So; that means, first we have to consider the trajectory first you have to understand. So, here, if we take the on-state dynamics and if the on-state trajectory moves along this path, then it is going towards the switching boundary. If you take the off-state trajectory and if the off-state trajectory, whether is it coming towards it or is it going away from it?

So, if depending upon that there can be many various you know condition whether both side the trajectory on-off trajectory are towards the switching boundary or one side it is towards the other side it is away or it can be the third possibility both side can be away. So, these concepts are actually explained in elements of power electronics book.

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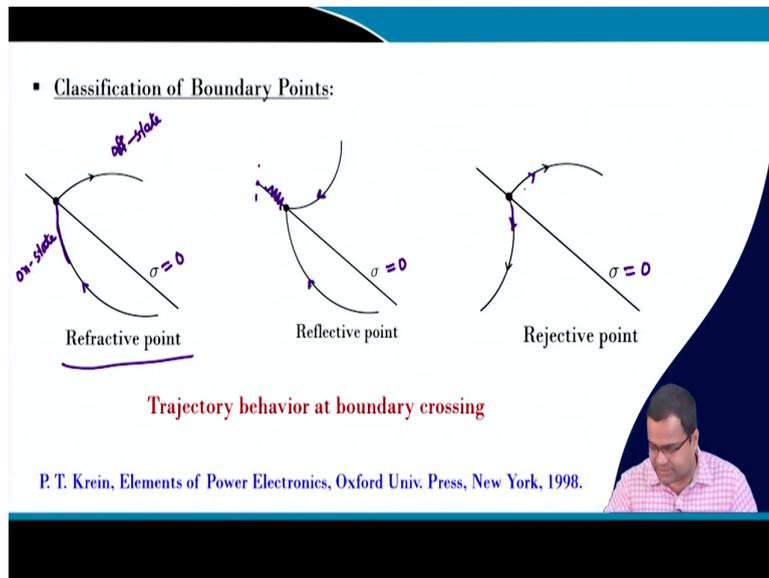
And if we classify; that means, as I said, this is my switching line, which is equal to 0 this all should be equal to 0 then, the trajectory will be towards in one side the left side it can be right side. Trajectory is going towards the switching surface, but that is my on-state trajectory, but my off-state trajectory is going away from it so; that means, this is called refractive point and such kind of concept will be used to achieve time optimal recovery.

But if both side trajectories are towards the switching surface then, it will slowly you know kind of you will achieve the sliding motion; that means the trajectory will chatter and it will go towards. Let us say, if this is my origin point, it will go towards origin ok so; that means, both sides then the chattering will start the actual switching will act. And the third possibility if both side trajectories are moving away, then that is called rejective region and we must avoid such region otherwise, it will be unstable.

So; that means, the rejective region we should not place a switching surface or we should not consider a sector of 2-dimensional plane where our surface is placed in the rejective region. And if you take any initial condition there, then your trajectory is going will go unboundedly

and it can lead to like particularly for a boost converter maybe complete collapse of the system or it can damage the other devices.

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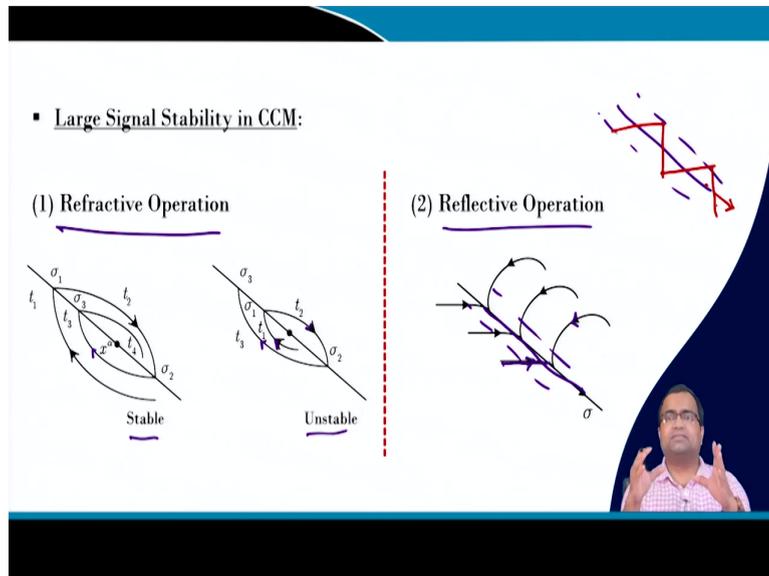
So, the last signal stability in the refractive region we can think of. It will take like overshoot undershoot, but we will take more cycle and unstable in the rejective region right. And in the refractive region it is stable, but it will be overshoot undershoot and the unstable case in the rejective region and the reflective operation you know.

So, in the reflective region also, if you do not take the sequence of switching properly, it may so happen that you know you start with on-time and then off-time; that means, if you choose a wrong control logic, then it will become unstable. So; that means, the only refractive region is not sufficient. The switching control law is also important; what kind of control law you are taking. In the reflective region, both side the trajectory are approaching. That means, it will slowly move towards this line and you can actually create a hysteresis band so that you know it will like this.

So, it is your switching surface both sides. So, the trajectory will move like this. It will move like this. It will slowly move like this and going towards the desired point and there actually we achieve sliding motion.

So, now here, we are considering we are going to implement current base this surface, the switching control, where one state is my inductor current minus the output current. So, whether you will consider output current or something else, that we will see. The other state will take output voltage error. So, our switching boundary again the current error plus some gain into voltage error and this is something similar to a proportional gain, because this looks like your i l minus i 0 plus k p into v 0 minus v ref right.

We can rearrange. We can write in an alternative way. We can write i 0 minus i l plus k p in to v ref minus v 0. So, if we multiply with a minus sign here, as if we have multiply with a minus sign to get there, because it will look like actual error voltage. Then, our switching control has to be accordingly modified otherwise, as I said, it is going to rejective region and thus trajectory will move away.

So, this two control logic should be just the opposite, because we have taken. So, you can use any of them, but accordingly we have to choose the switching control logic. Now, the red one is the one which is represented by this surface, this surface, but if we use this surface and if we make. If we design the control law in such a way, ok this is my switching logic sigma equal to 0 and if we force the trajectory like reach there, sorry. If we force the trajectory that you reach there once you cross it, then you come here.

So, if you do like this, then it will result in infinitely fast switching and this is known as chattering behaviour right chattering and that we must avoid, because if there is any

chattering, because we are using a practical converter with practical switch. So, it will force the device to operate at its hard limit turn on and off very rapidly and it can damage the device and it can you know. So, we must avoid; that is why we need to incorporate a hysteresis band.

So, this will introduce a dead time. That means, once you turn off, you provide some time and then again it will turn on and this can be either implemented by a direct time base control like we will discuss in the subsequent lecture or it can be introduced by directly by on the trajectory by means of a variable which is a hysteresis band.

So; that means, we can introduce a band, and this is usually that in case of hysteresis base implementation and if we introduce a time then, we can think of a constant on-off time implementation where we are putting a time you know dead time ok.

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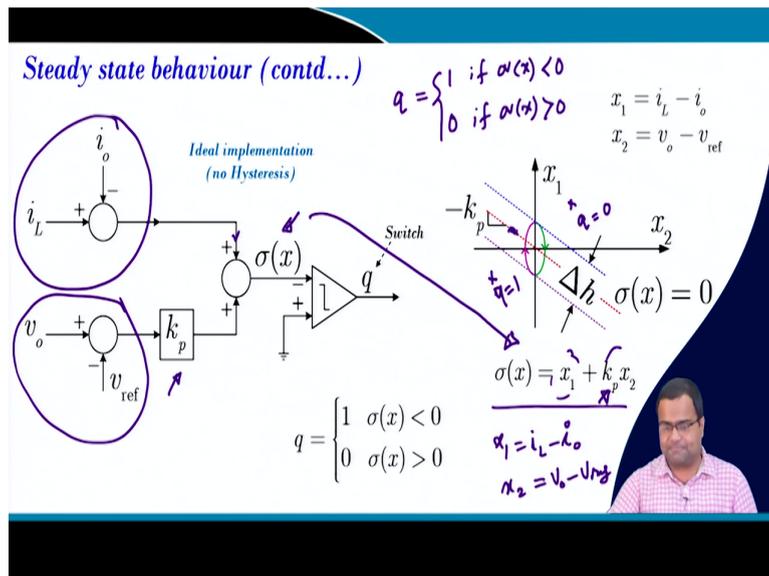
So, the steady state behaviour sigma x. Now, if we want to implement our ideal switching surface and you see, since, we have taken x 1 to be i l minus i 0 and x 2 to be v 0 minus v ref. So, this is my i l minus i 0 and this is my v 0 minus v ref and then, we have a k p here. So, this is my proportional controller and these two are added up. So, these two are added up and this is my sigma x right. So, this is my sigma x.

Now, what is our switching logic? Here, the switching logic is this. q will be equal to 1, if sigma x less than 0 or it is 0 if sigma x greater than 0 that is my switching logic because; that

means, this side I will take q equal to 1 and this side, I will take q equal to 0 and this is my switching logic.

And we can implement using MATLAB, but you will find a real difficulty, because you have not inserted any hysteresis band. You are forcing computer you have computer if you want to simulate to operate or compute at the hard device, because computer will have a finite step solver time; that means, the time has a minimum resolution. So, it will try to hit the limit, because it will continuously turn on and off within this limit and that will slow down their whole simulation.

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So, the ideal switching logic is practically not recommended to use. It results in very fast switching at steady state, which is not desirable. It can damage the switch. There are limits on the practical on-off time of the device; even for simulation. Also, we have a limit, because of the simulation step size.

And in practical component this can lead to component failure, because of heating effect and you are turning on and off very rapidly and first of all this may lead to very you know like a chattering behaviour will lead to you know EMI problem. Because even if we put a smaller hysteresis band, then the switching frequency can be very high. So, we need to set the right hysteresis logic.

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So, adding a hysteresis band. Suppose, as I said we have chosen this sigma x. Now, divide into two part. One is sigma 1 x which is parallel line on the top and the other is sigma 2 x which is a parallel line on the bottom, because this two are parallel line and they are separated. And the sigma 1 x is crossing this x on axis at a o a point and sigma 2 x is crossing x one axis at b point. So, we can write and we need to find what is the equation. We know that sigma x is equal to x 1 plus k p into x 2 and that equal to 0.

Now, sigma x certainly: it is a parallel line, and sigma x is passing through origin. But, sigma 1 x is not passing to origin it has a parallel line, but it is that is why for sigma 1 is we need to add this off set and you see the all this parameter will same, because it is a parallel line. Sigma 2 x is the same parallel line, but it will have a different offset, because it is here and how to find out this off set.

So, at point a, where sigma 1 x intersect equal to and that is already equal to 0. So, at point x 2 equal to 0. And if you substitute here. And at point a, x 1 equal to a; that means, at this point you are getting x 1 equal to a and x 2 equal to 0 and if you substitute, you will get c equal to minus a.
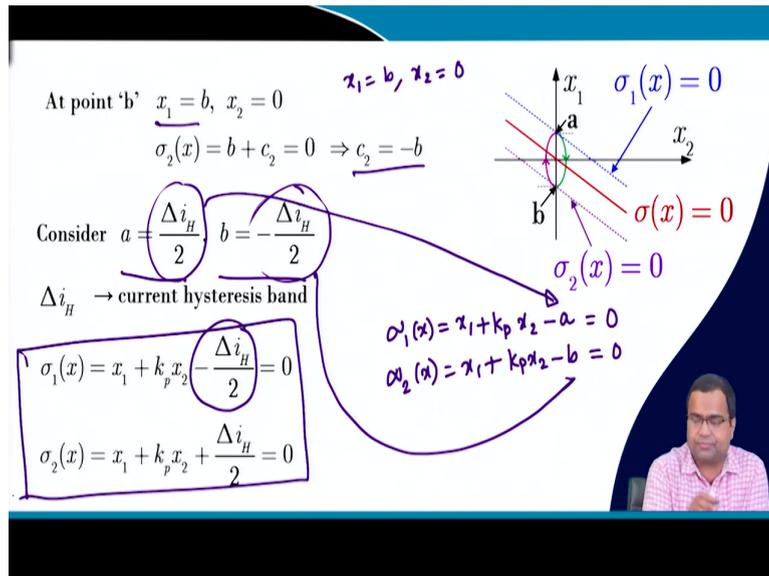
Similarly, at point b if you substitute; what you will get x 1 equal to b and x 2 equal to 0. So, you will get c equal to minus b 2. Now, suppose x 1 axis is my current axis. So, I want to introduce a current hysteresis. Upper limit is delta i H by 2 and the lower limit is minus delta i H by 2. So, that is why substitute an equal to this and b equal to this and then, you know if we put it into our earlier form, because you saw what we are getting is here, c 1 equal to minus a and we substituted an equal to this.

That means we have to first write down what was our sigma 1 x. It was equal to x 1 plus k p x 2 minus 1 and that is equal to 0 and we found sigma 2 x is equal to x 1 plus k p x 2 and you can see it is minus b equal to 0. Since; we are taking an equal to delta i H by 2, we are substituting here and b equal to minus delta i H by 2 you substitute here. So, we will end up with these two equations right.

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These two equations. And then, what will be our switching logic; that means, our switching logic will be since you can see what is the requirement; that means, your this side trajectory our sigma 1 x for q. What is my q logic; that means, if the trajectory cross this; that means, when sigma 1 x is greater than 0, then we should turn off the switch right; that means, sigma 1 is greater than 0 is nothing but if you write it here, sigma x is greater than delta i H by 2.

And similarly, sigma 2 x should be less than minus 0 and which will lead to this equation, because the off-state trajectory when it hit here, we should turn on the switch right we should change the logic.

So, now, we are going to implement what is how to implement the practical switching law. So, we saw the ideal switching law q equal to; that means, the q equal to 1, if our sigma x is less than 0 and it is 0, if our sigma is greater than 0. So, this will be modified to q equal to 1, if sigma x less than minus delta i H by 2 and it equal to 0 if sigma x greater than delta i H by 2 and that we have seen in the previous lecture ok previous slide. So, here sigma x.

So, this difference actually if I take the difference here, at any point this difference is nothing but or delta i H by 2, because we are setting this band here ok.
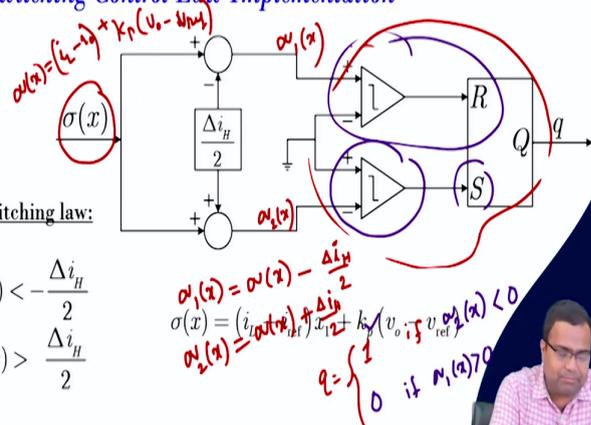
So, it is a current hysteresis band and how to implement. Again, the control law sigma x what is this. Here we know, the sigma x is in our case i L minus i 0 plus k p into v 0 minus v ref ok that is sigma x. And then, we are adding this band and that we have discussed; that means, sigma x minus; that means, what was our sigma 1 x. It was sigma x plus if we go back.

What was our sigma x? See, this is my sigma x minus delta i H by 2 and this is my sigma x plus delta i h by 2; that means, So, this should be minus; that means, we should choose this to be minus delta i H by 2 as sigma 2 x is sigma x plus delta i H by 2. So, you can see. So, this is my sigma 1 x and this is my sigma 2 x and they are compared with the hysteresis logic here.

So, this is a hysteresis logic; that means, what we got q equal to 1, if sigma 2 x is less than 0 you see this is a logic that it will set it will set it will become 1. And will be 0, if sigma 1 x is greater than 0 and this is a logic ok. So, we can implement this logic and you know we can realize this logic.

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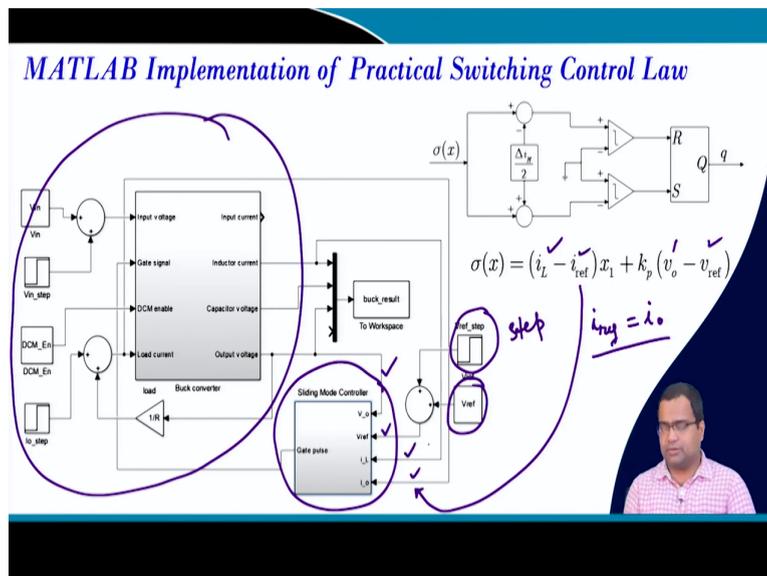
Now, we want to show I want to show the MATLAB implementation. So, I did a little different way in MATLAB. What I did? Here again, a sliding mode controller again this is my reference voltage. We can apply a step this is for step transient I can do this is my reference voltage and I am taking the output voltage. So, this block I have presented multiple time that we have developed. So, it is known.

This controller we are going to discuss how are we going to implement this controller and you can see there is this i ref i have chosen to be load current. So, this i ref I have chosen it is nothing but load current, but it is not necessary. You have to choose the load current always, because there are alternative way of representation and I need v 0. So, this is my v 0 v ref this is my v ref i l this is my i l and i ref this is my i 0 right.

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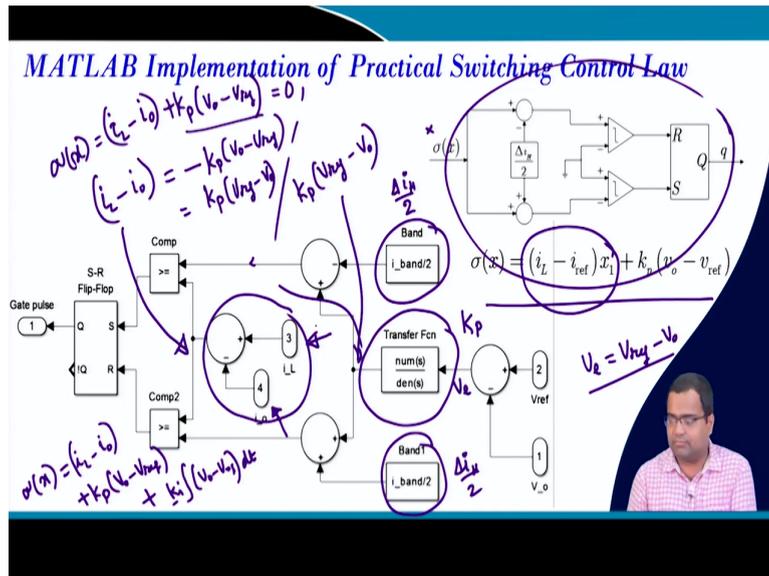
So, if we go to the next. Next, what I am doing. Here, I am using a different implementation. So, here you can see this band which is my delta i H by 2 the same band delta i H by 2 delta i H. You can implement the way here I have explained no problem, but I have implemented a different way. So, I can change this way and do it whatever it is there this transfer function is a controller and typically I am choosing this to be a proportional control.

Because here, I want to put it like a standard the voltage loop error voltage. So, this is my error voltage. In this case, I have used a conventional notation of error voltage v 0 minus v ref minus v 0, then it is going to a proportional controller and then we are adding this band and an actual current. So, I have taken here. So, this current; that means, I have broken this sigma x into two parts. So, in this implementation, this particular signal is nothing, but your k p into v ref minus v 0.

That means if I talk about sigma x which is my i l minus i 0 plus k p v 0 minus v ref and that at 0 we want to achieve right that is equal to 0. So, if I take this part; that means, i l minus i 0

is equal to minus k p v 0 minus v ref which is nothing but k p into v ref minus v 0 and this is exactly I did it here ok and I kept i l minus i 0 here.

So, this term is my this term here, and then I have added the hysteresis band with this quantity. You can implement in different way you can try out in MATLAB. We have explained multiple way.

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Now, I want to show the simulation result.

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So, I just want to go to MATLAB simulation.

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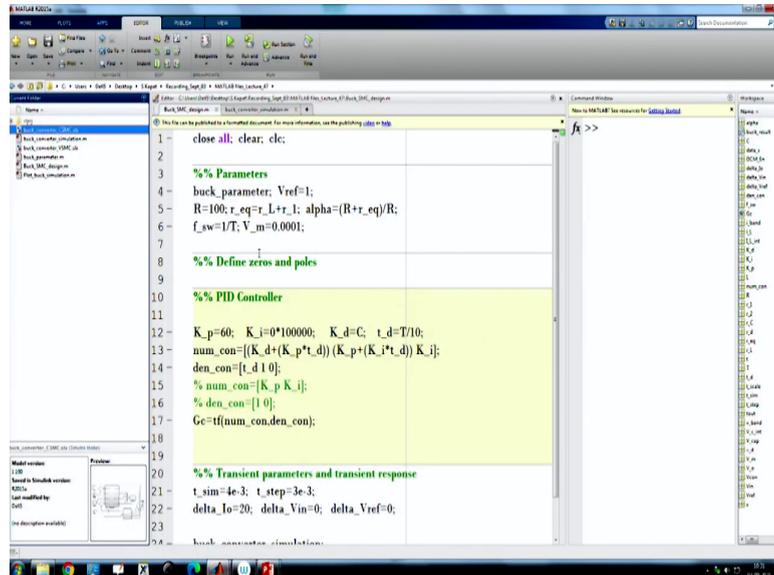
So, first I want to show you that this is the implementation that I talked.

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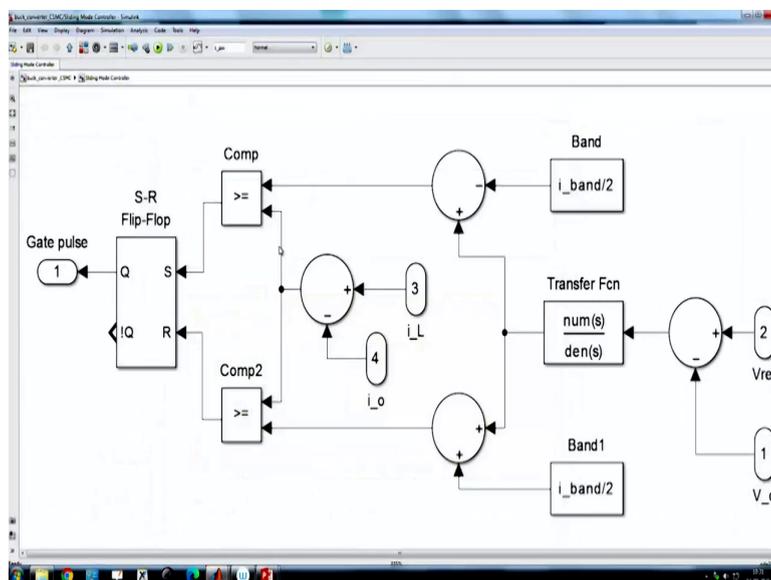
I have just discussed. So, this gain I am setting from externally.

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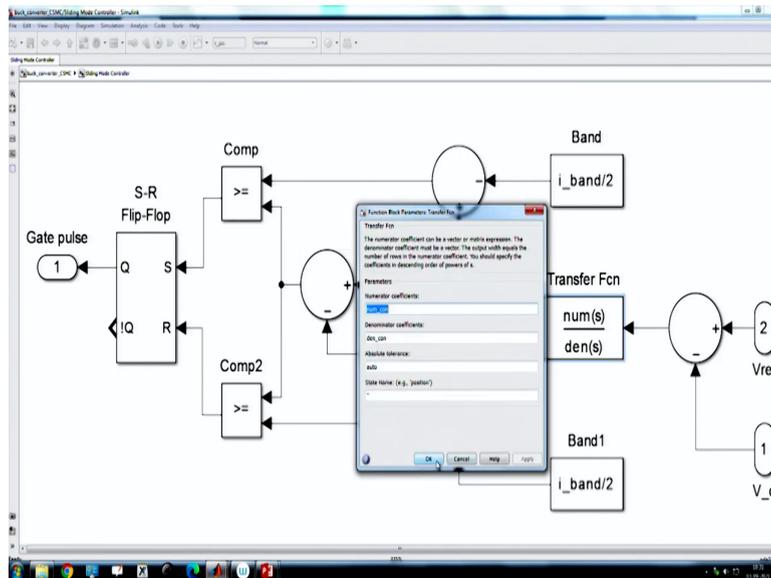
And this is the logic numerator denominator and this is my band.

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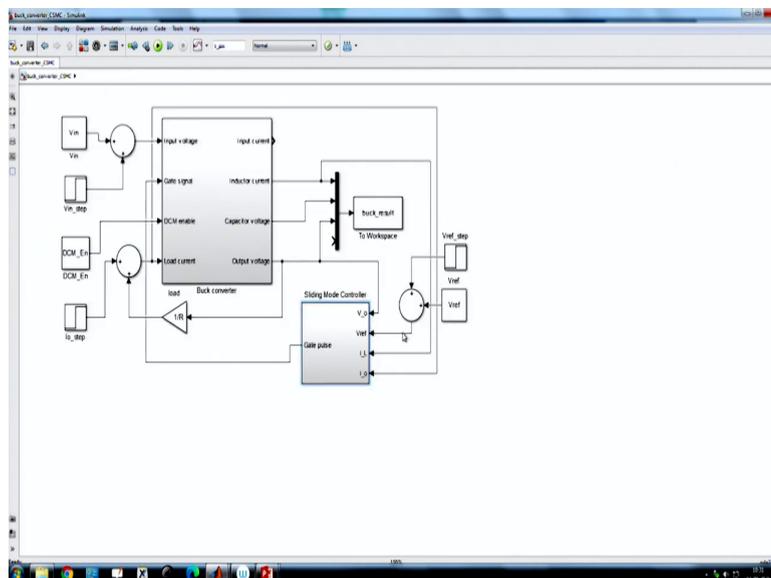
And if you go to top block, this is my realization.

Now, I want to go. So, this is my buck parameter. You can take an ideal buck to start with. You can put all the parasitic to be 0 there is no problem ok. So, you can take all the parasitic to be 0 all the parasitic to be 0 ok and 12 volt input 1 volt output; a standard form and here, you know you can. This alpha is not required.

So, you can remove this path. Only load resistance should be sufficient. you do not we do not consider ramp. So, it not required. So, poles and zeros are also not required. Now, though I am showing a controller it should be a controller rather than PID. So, this K p i am choosing

60. So, forget about K i K d and t d, because I am initially interested in only proportional control and I have chosen K i to be 0. And here, I am using a surface you know I just comment it.

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This is the control logic I am taking ok. So, you can keep it somewhere else just to avoid any confusion ok. So, I can take this thing put it at the bottom, because I may not need it. So, this part when I require, I will put it. So, I do not need any K p or K d ok. And here, I am just considering yeah. So, I am not considering any integral action. It is just initially a proportional control and I am applying a load step transient of 20 ampere.

So, initially my load resistance is 100 Ohm; that means, my initial current was 1 volt by 100 ohm means, 10 milliampere and that is changing the current is changing from 10 milliampere and it will going it goes into 20 ampere ok and we want to see the response.
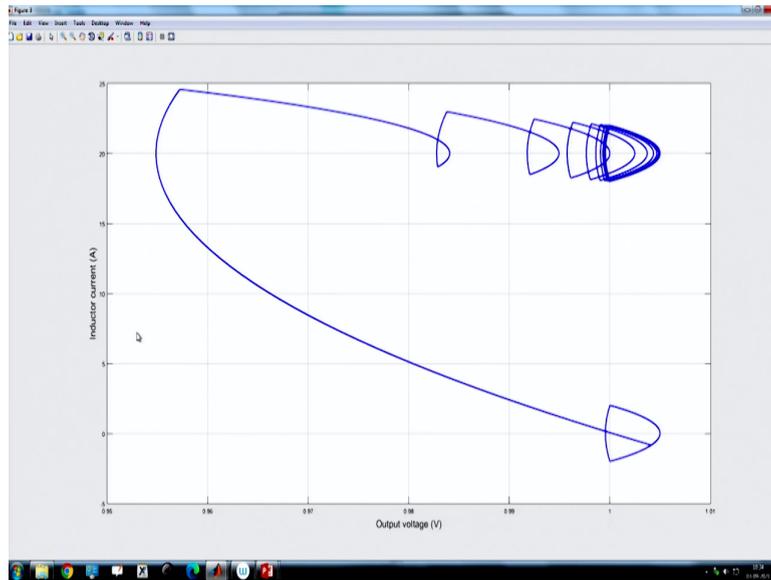
So, let us see the response to this scenario. So, now, this is the phase plane behaviour. So, this is my output voltage access and I am not considered any integral action. And you can see it is going first transient here, this is the inductor current and then, it takes multiple switching cycle before coming back.
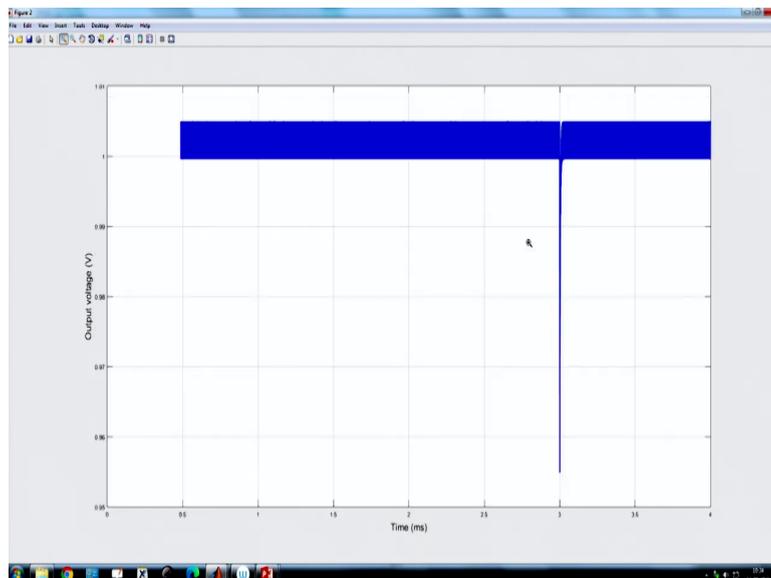
And if you go to the output voltage wave form, because I have discarded some of the initial transient.

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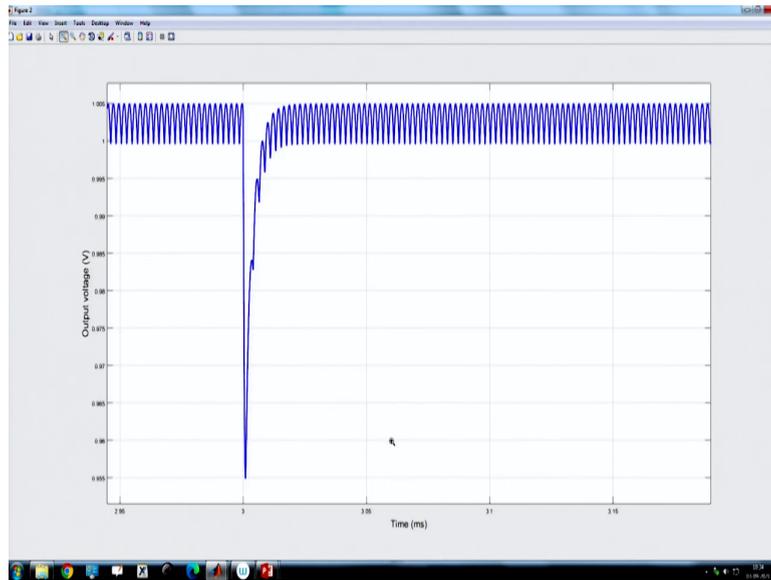
Because we want to show the phase plane correctly.

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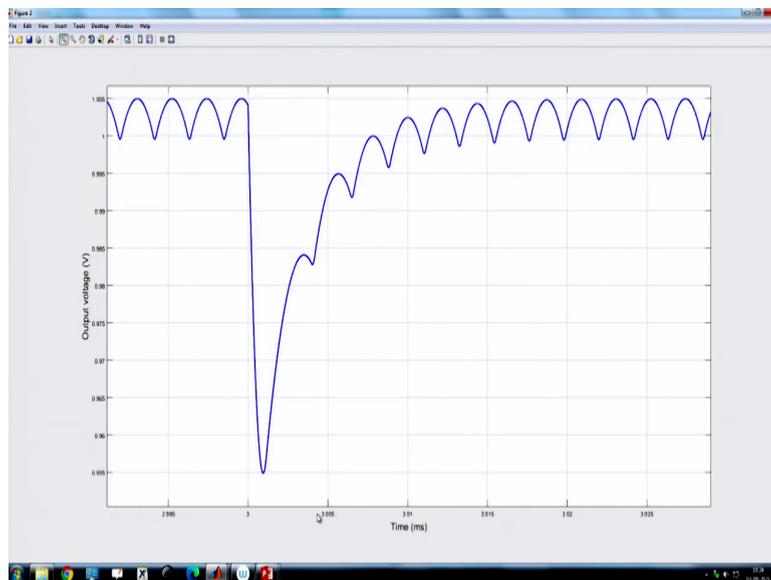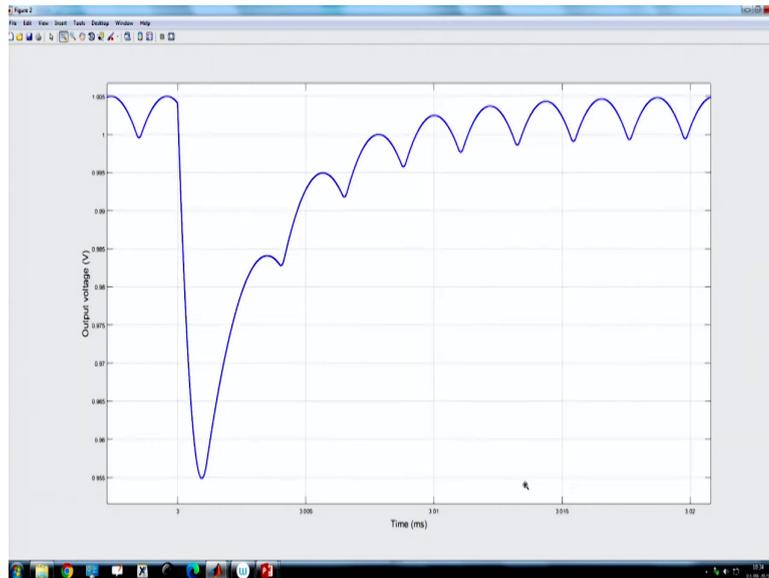
You can see it is taking like initially. It is turned off coming here and then; it takes some more cycle before it goes to steady state.
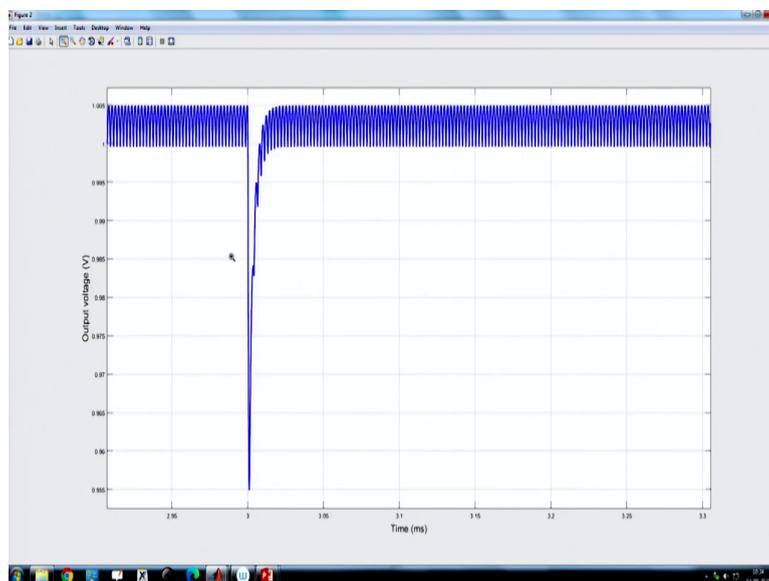
Since I have not considered any integral action that is why; there is a steady state error you can see.

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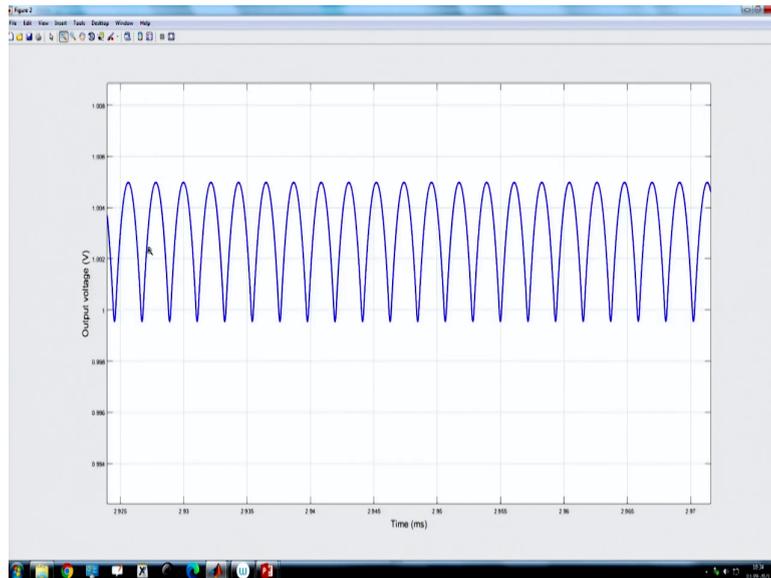
The average output voltage is not exactly 1 slightly above 1 ok.

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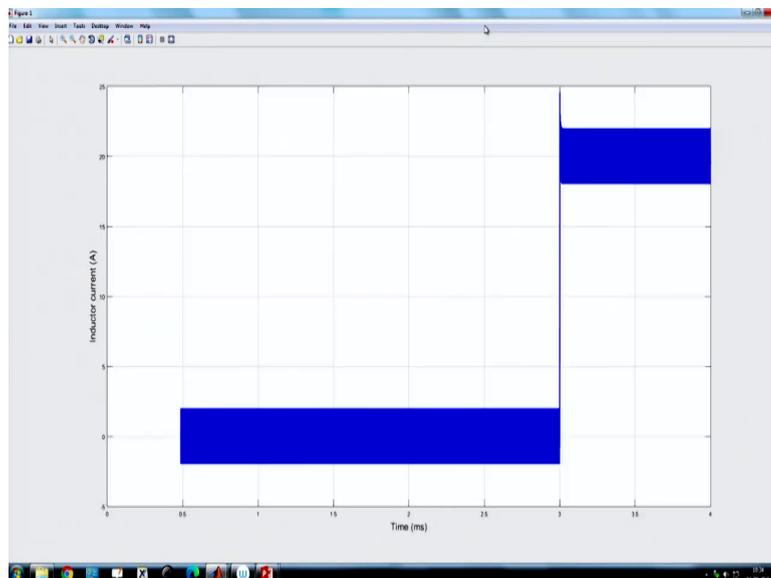
What is the current waveform? If you see the current waveform, current wave from look something similar ok.

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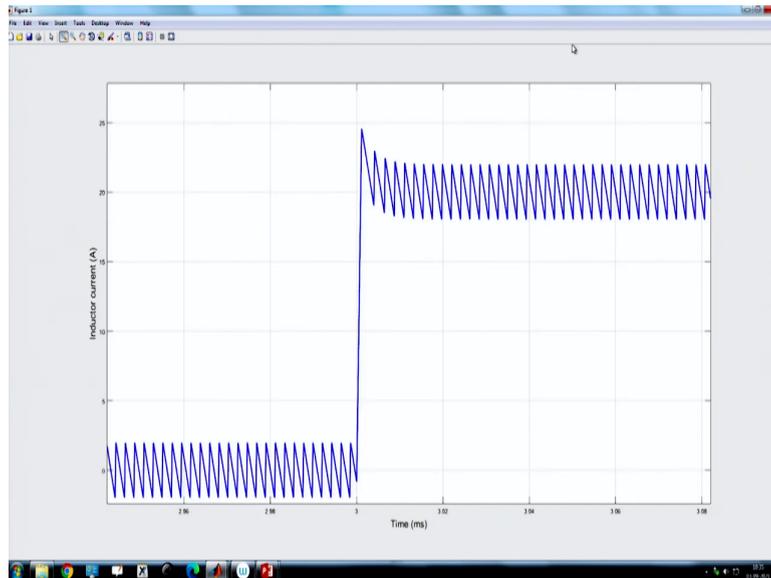
So, this is the current waveform.

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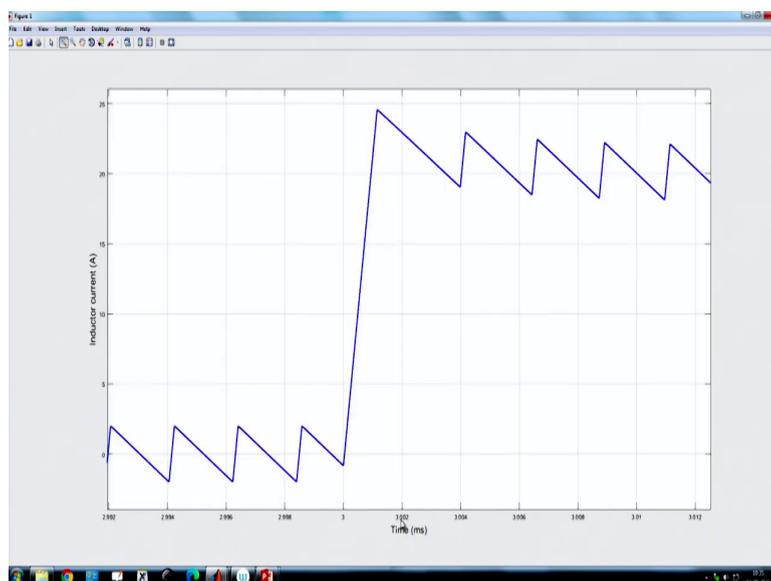
Now, I want to reduce the gain and see. Suppose I want to use let us say the gain to be 20 very smaller gain.

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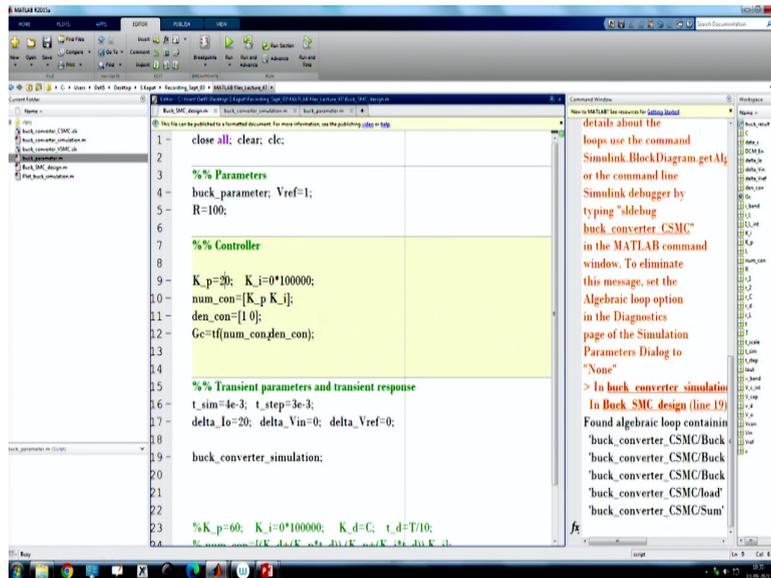
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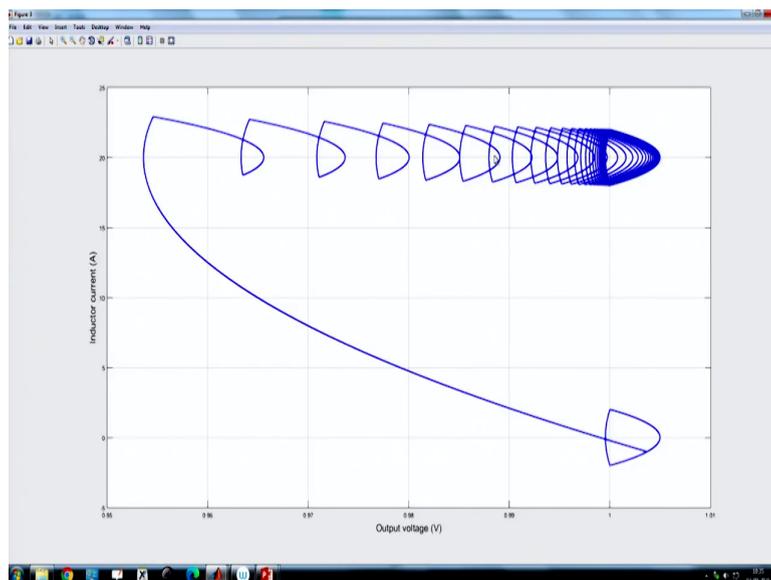
And I want to see how does the response looks like. And you can say it takes many cycles to reach there.
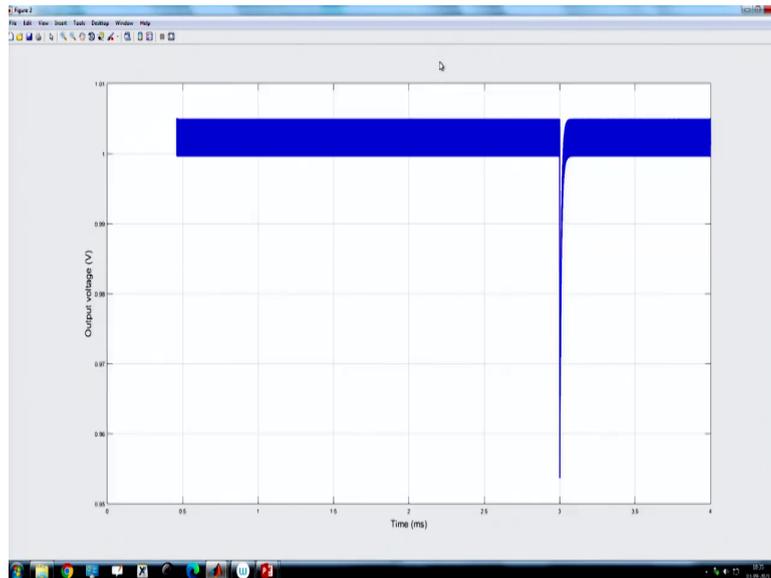
Many cycles. And it is evident from here that it will take multiple switching cycle to reach steady state multiple.
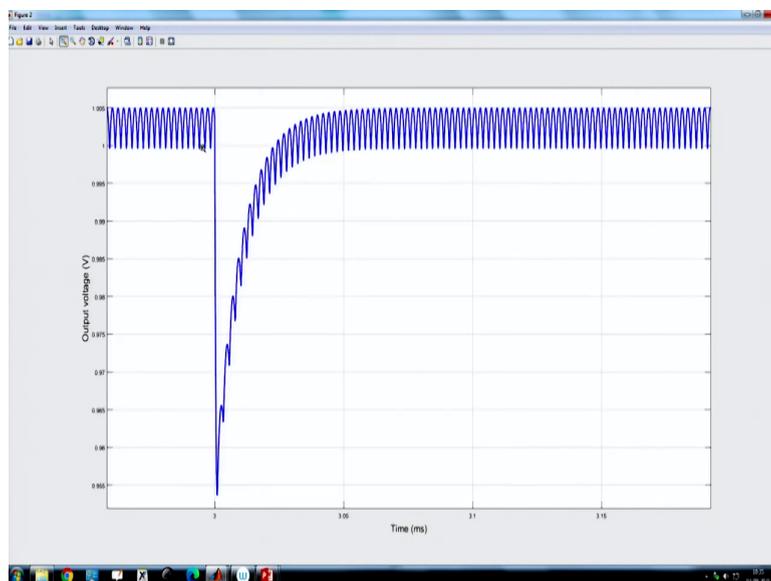
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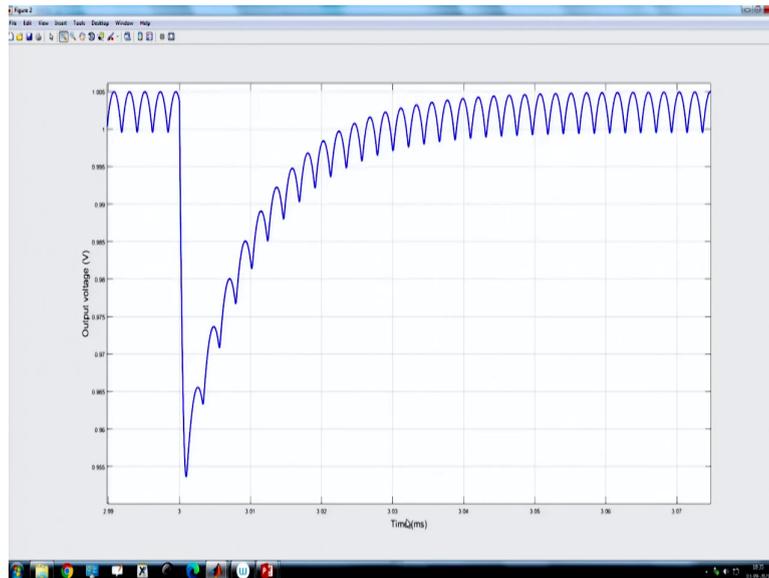
So, it is kind of over damped system. And this is something similar to what we discuss in this particular scenario in sliding mode control where we have considered. So, here a smaller gain. So, it will be overdamped and require more numbers of cycles. But we also want to see that it is totally in the reflective region where you know if you see that ok.

So, practical switching law, yeah. So, if you see the response to the phase plane, it is like a sliding mode. So, it is taking more cycles. It is like over damped. After turning on, it is taking more cycle, and it is catch coming steady state.

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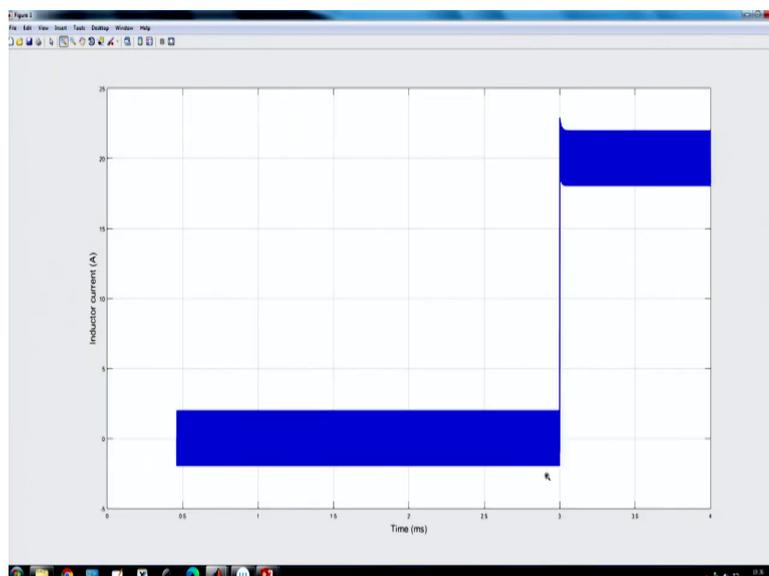
Now, what will happen? And there is no almost current overshoot. So, current overshoot is substantially reduced.

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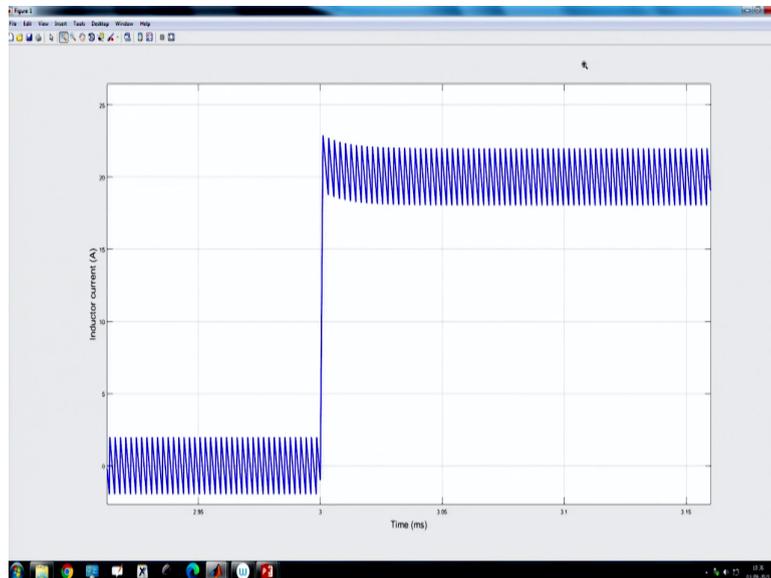
But it is taking longer duration.

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Now, if you increase to, let us say 100. So, instead of. So, let us make it 100 and see how does it responds.

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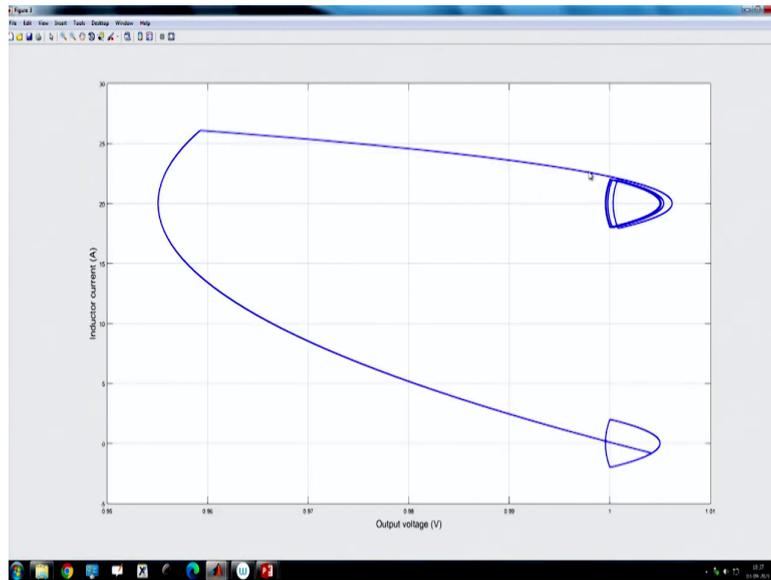
So, make it 100. It is slowly coming, you know.

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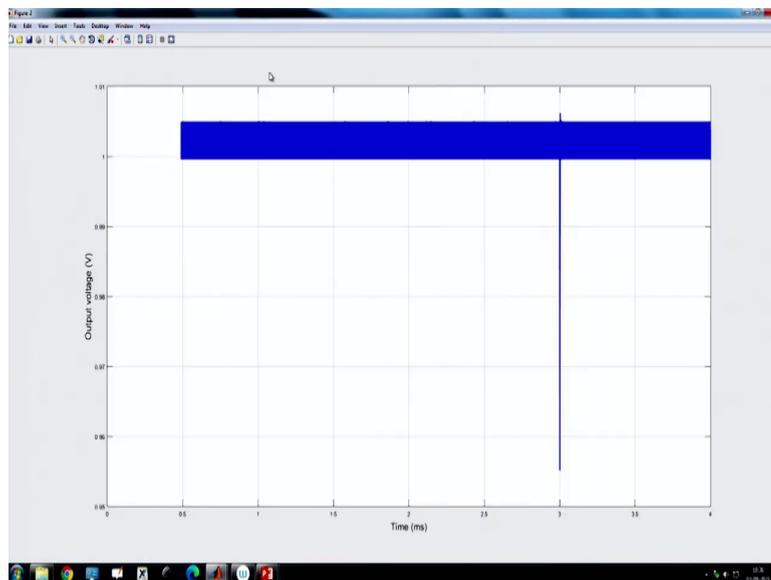
If you go and check the response.

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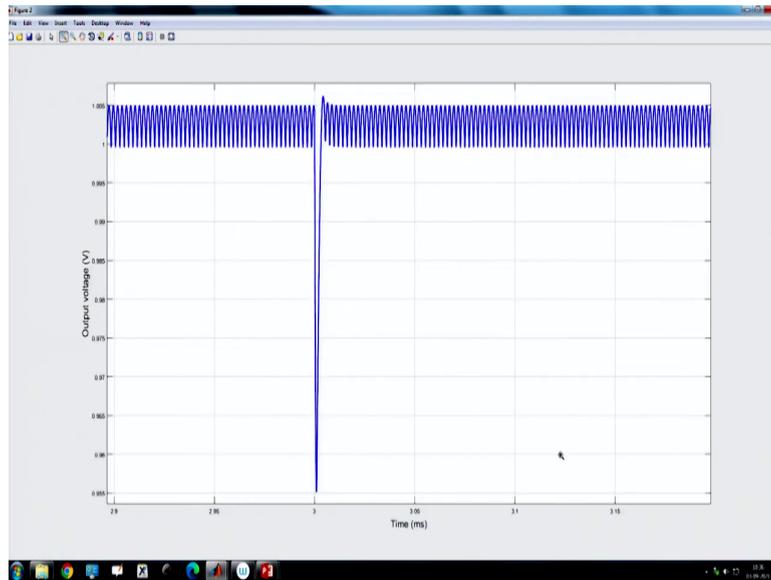
So, you will find there is slightly over damp.

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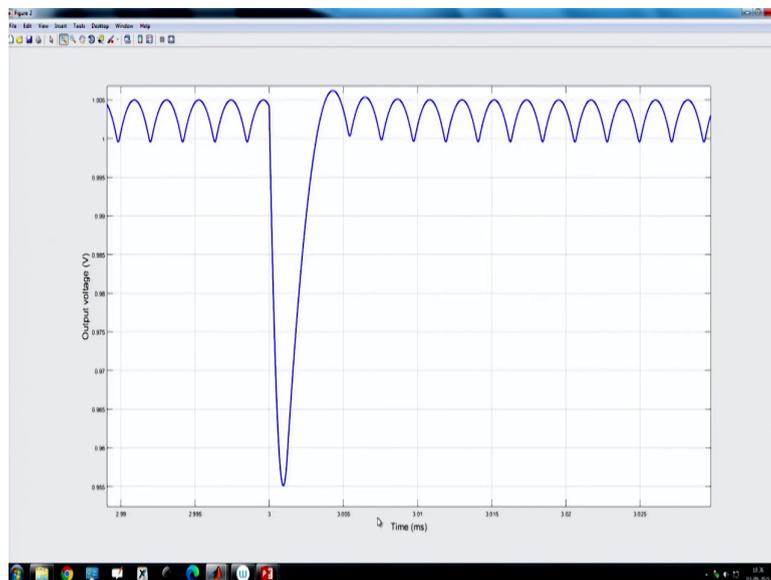
That means; it is not exactly one switching action like it is taking like here.

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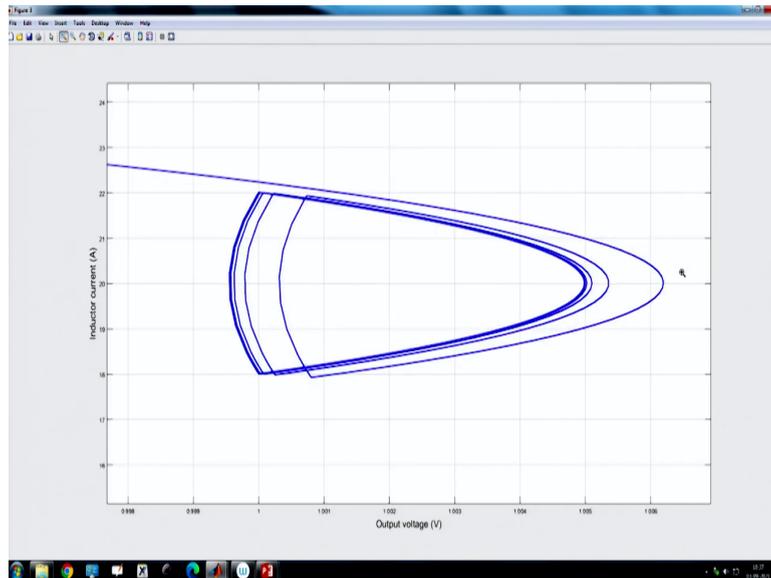
 It is taking few more cycles to reach steady state.

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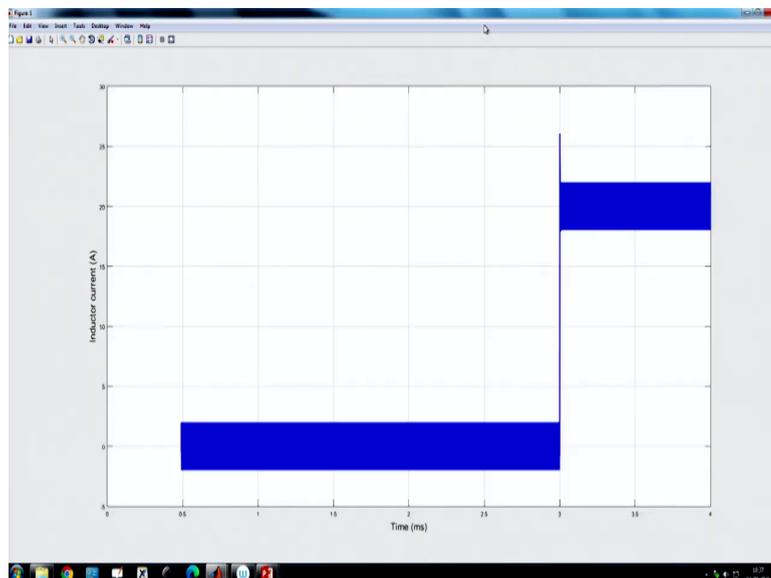
That means, it is very like you know small transient is coming here.

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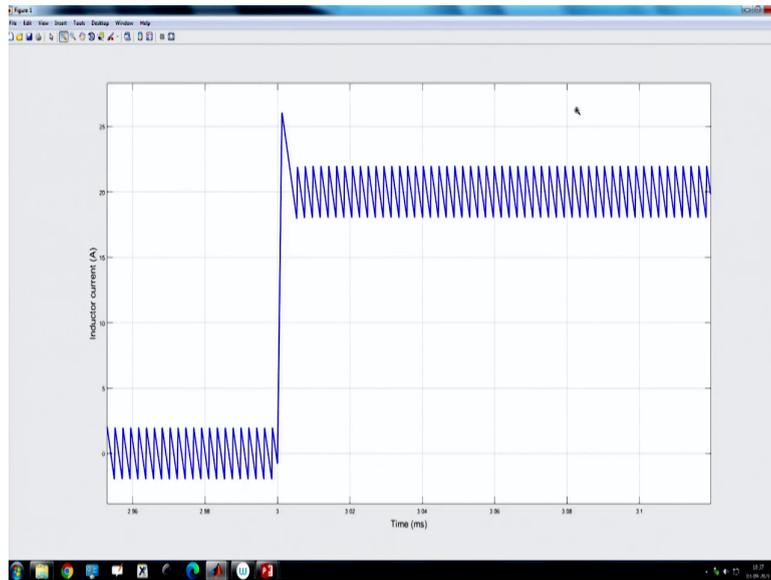
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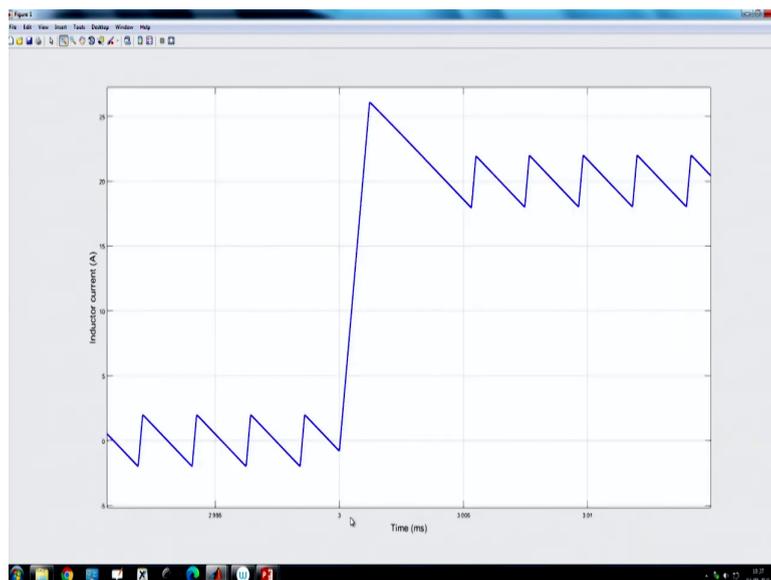
And the response is almost near to optimal response ok.

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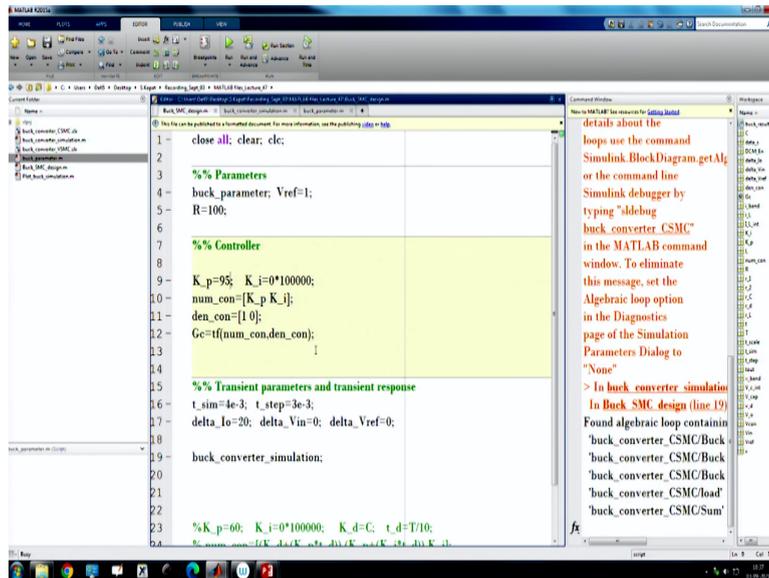
Now, if we reduce further, let us say we make it. Let us say 95 or. So, by that way, we will come almost close to the optimal response.

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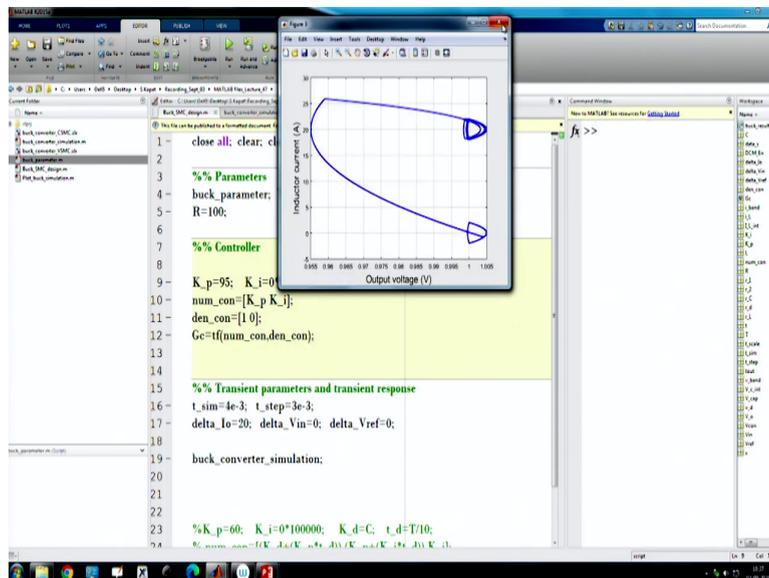
We are almost close to the optimal response.

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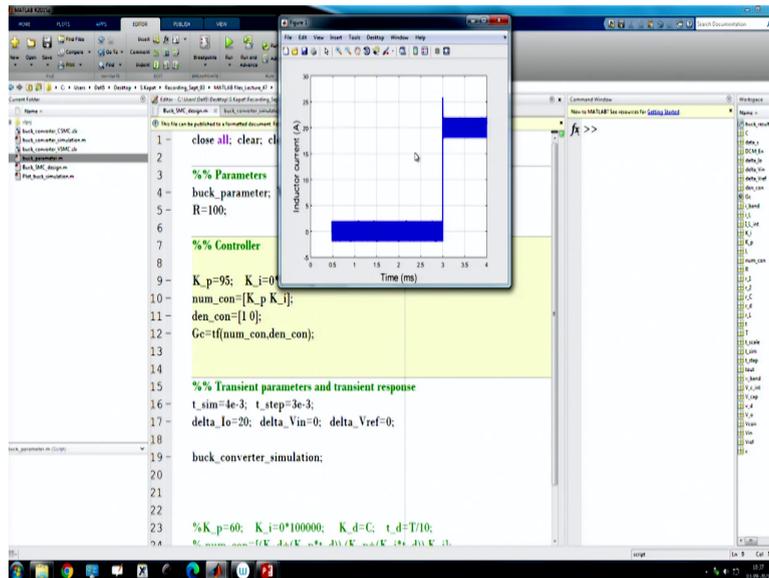
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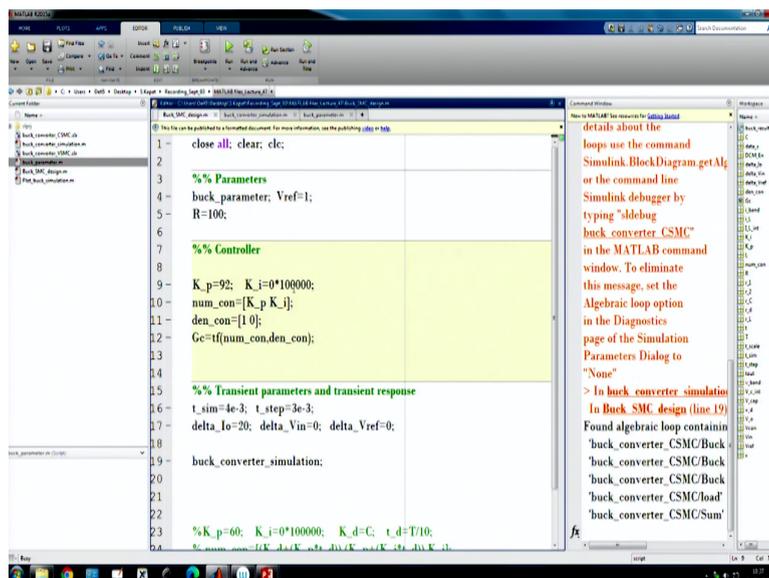
And we can further change the gain and see how does it looks like.

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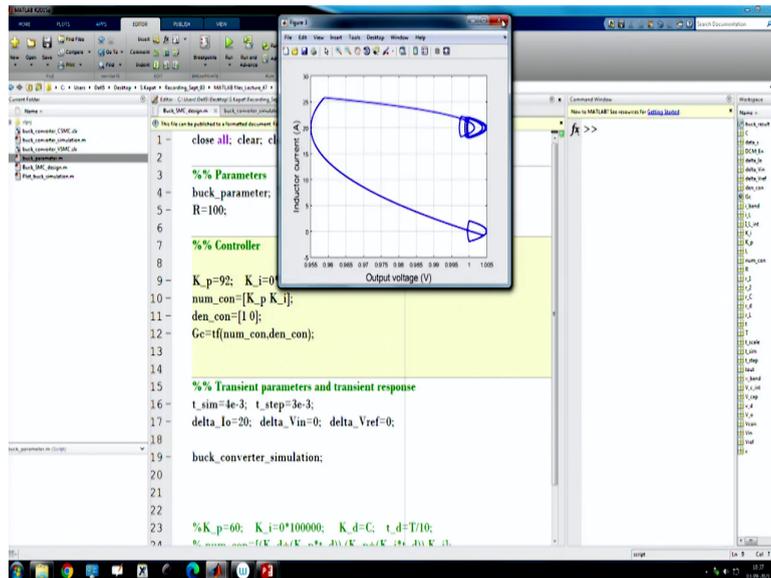
That means; we are playing with the gain and we are yeah.

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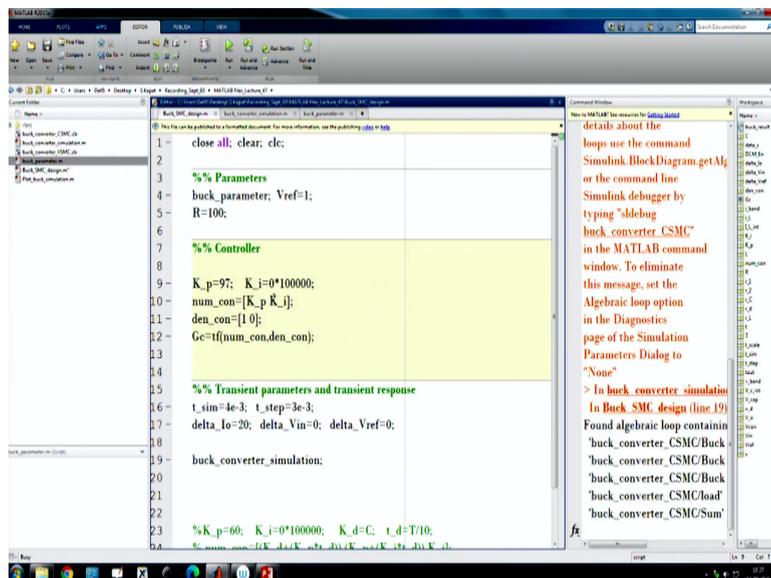
So, I think it is we should make it 97 ok.

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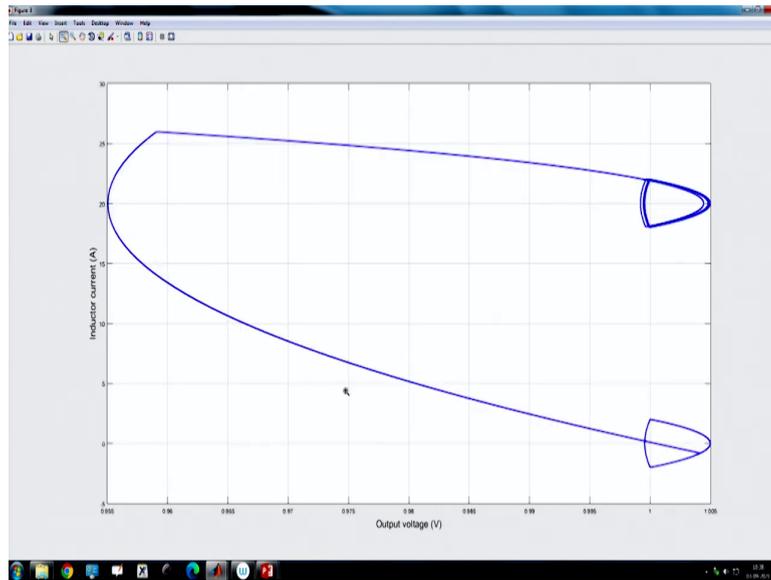
So, it is going and reaching steady state in one switching action. You can see it is going on then turning off and it is reaching here ok.

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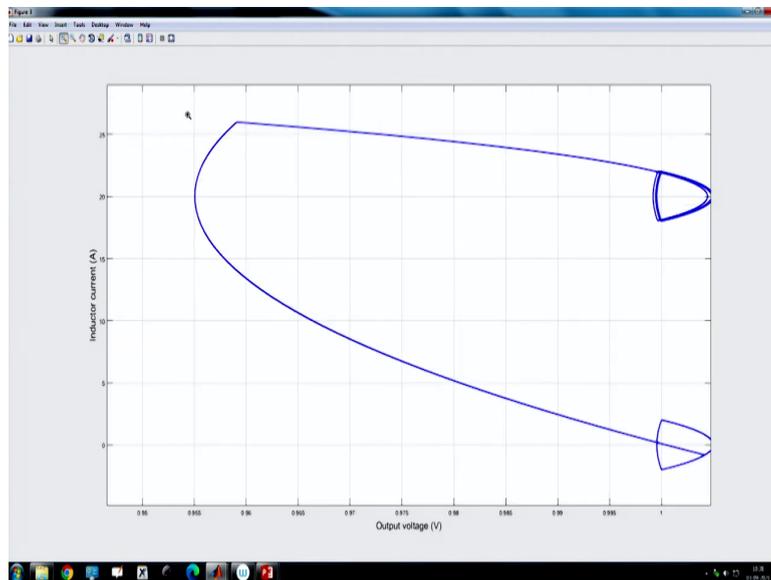
So, if I want to change the this portion say we will find much better yeah.

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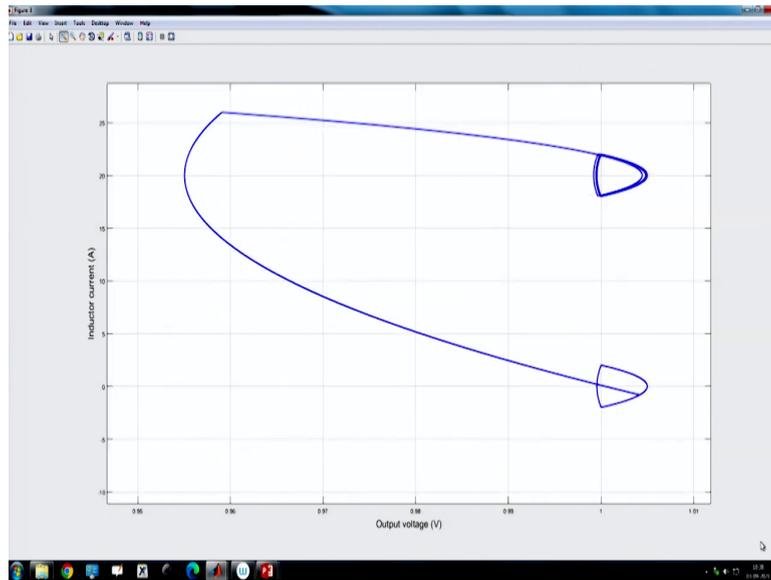
So, one switching action.

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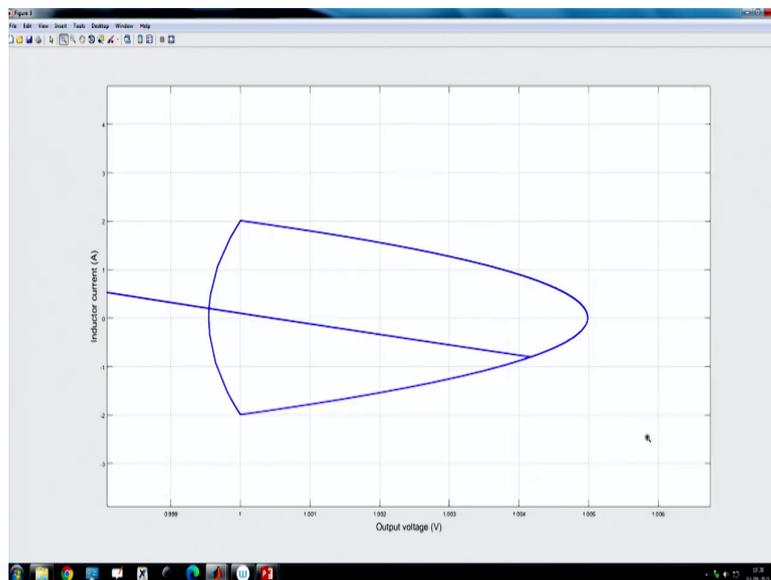
And this is a you know low bit is created like on off operation ok.

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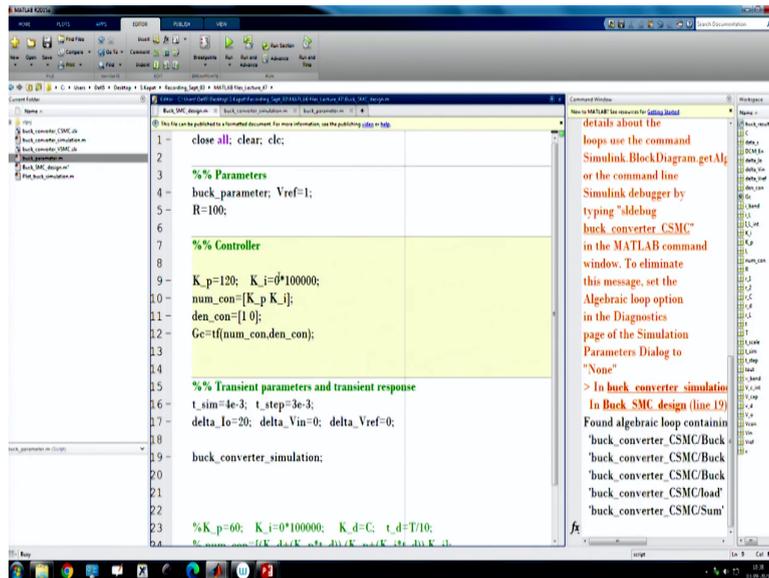
So; that means, now, if you further increase the gain to let us say 130 120. Suppose, you have chosen a very high gain.

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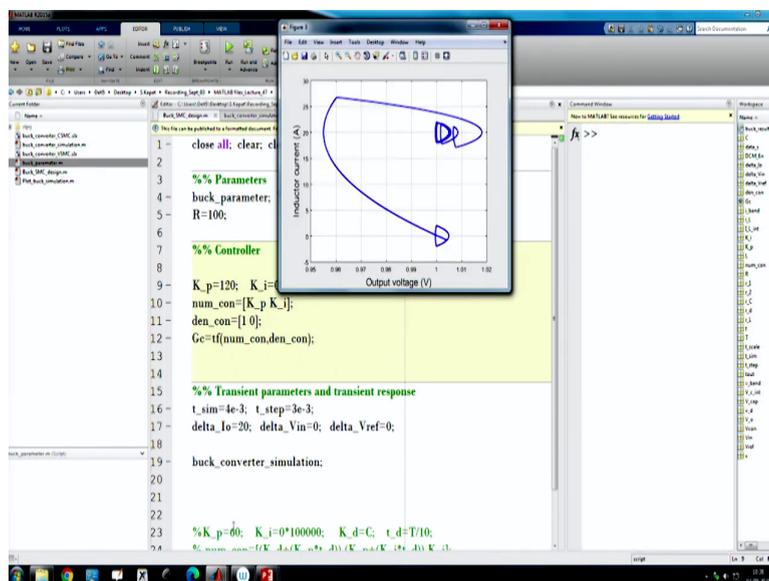
Then, you will find there is a high overshoot undershoot.

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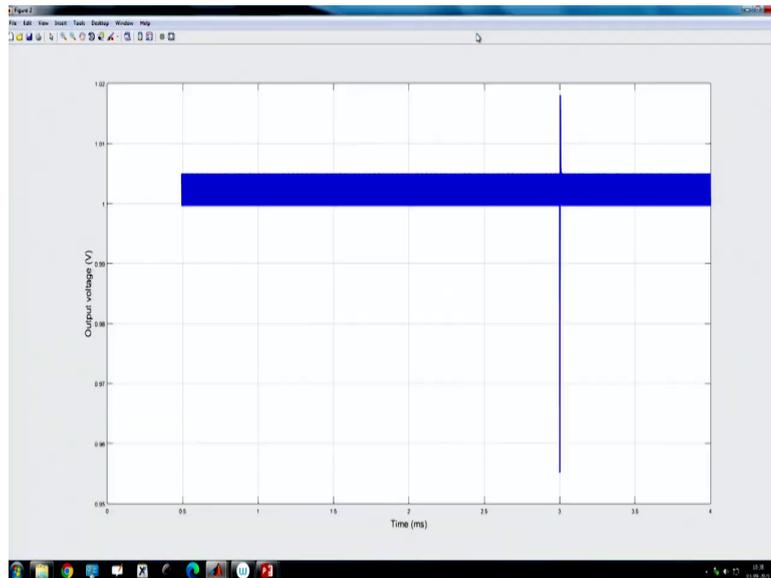
And the output voltage, you can see is a high overshoot in the output voltage.

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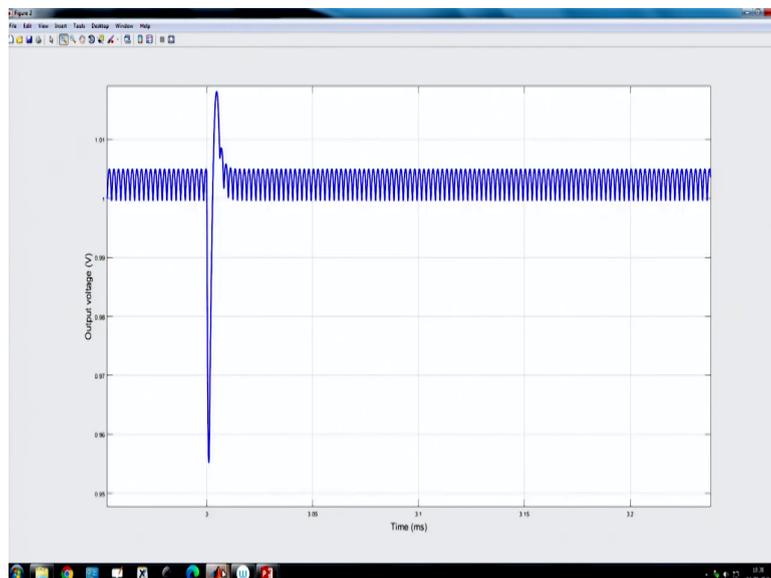
So, which is; that means, we are going we have not selected the slope properly. So, it is a slope selection.

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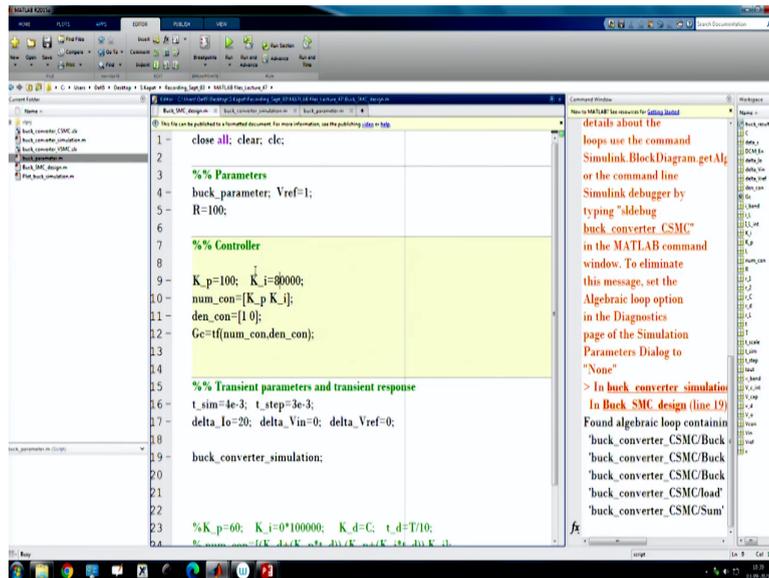
Now; that means, if we make close to 100. And now, if we initiate the integral action; that means, let us have the integral action and then, we see what happens.

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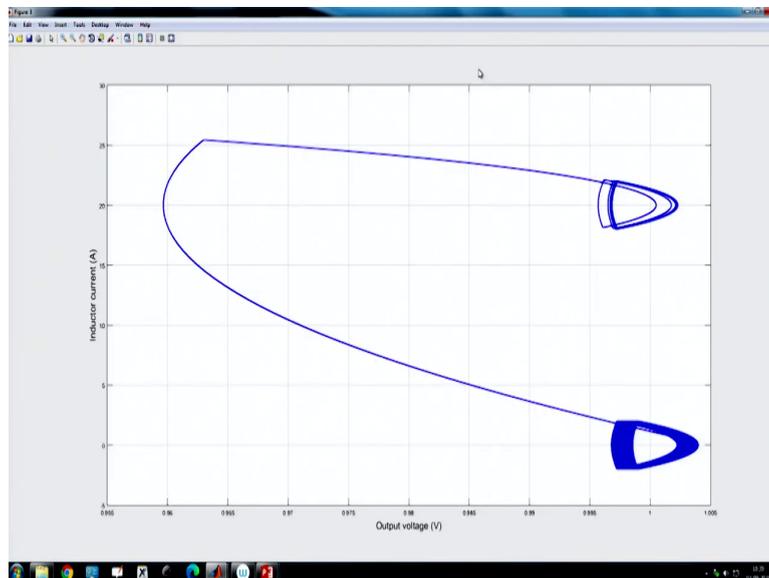
So; that means, what we are considering here, because of integral action, it is slowly coming to steady state.

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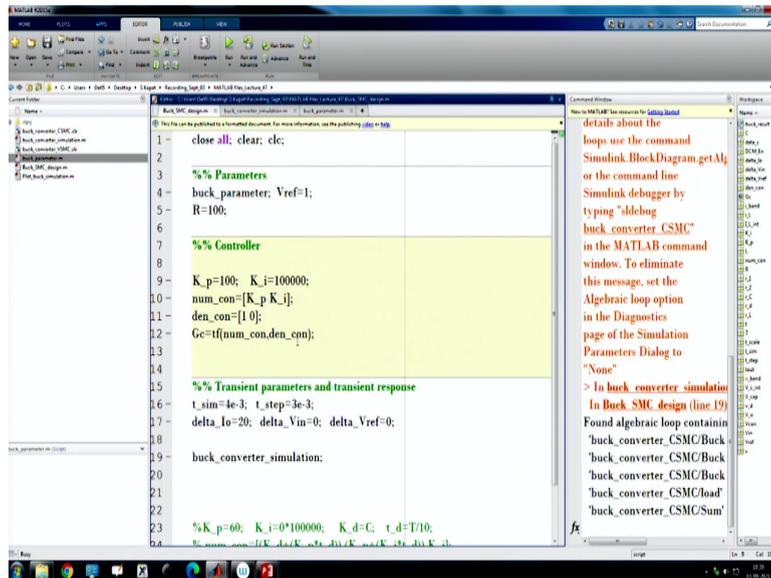
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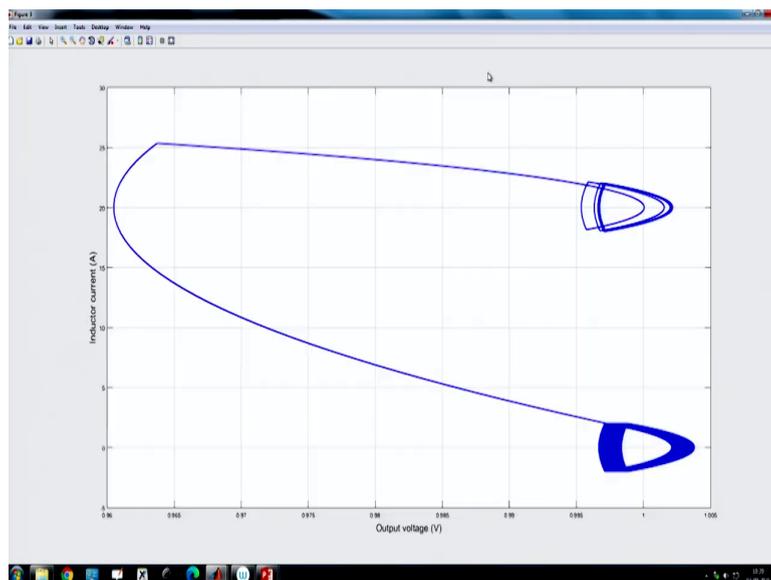
And if we increase the integral action, let us say this. So, we are getting close to steady state action.

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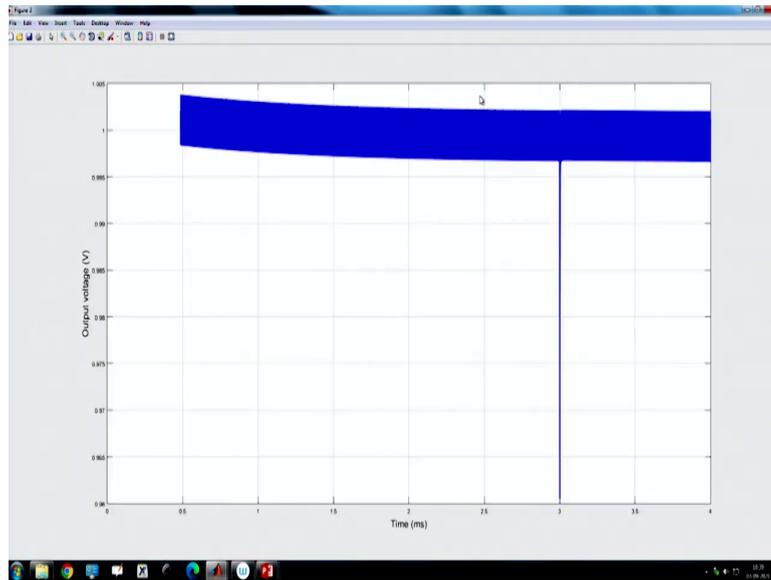
So, because of integral action, the voltage will slowly come average voltage to be 1 volt ok. So, like a one forth.

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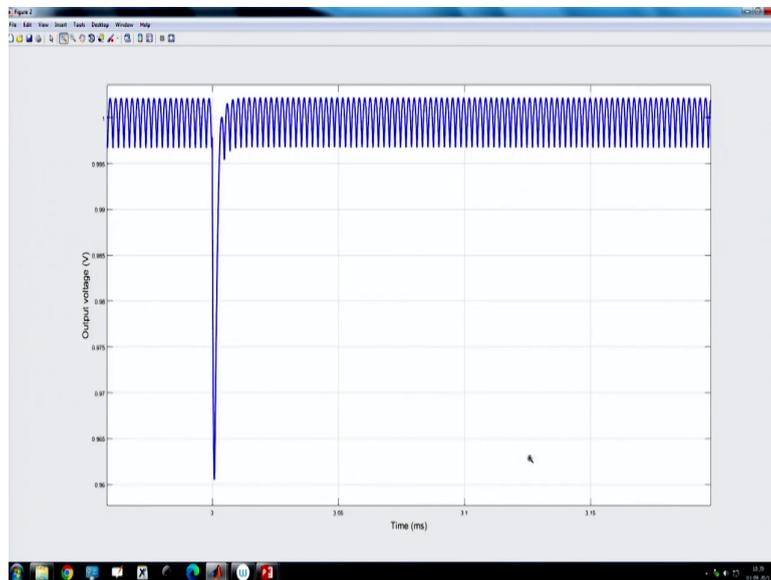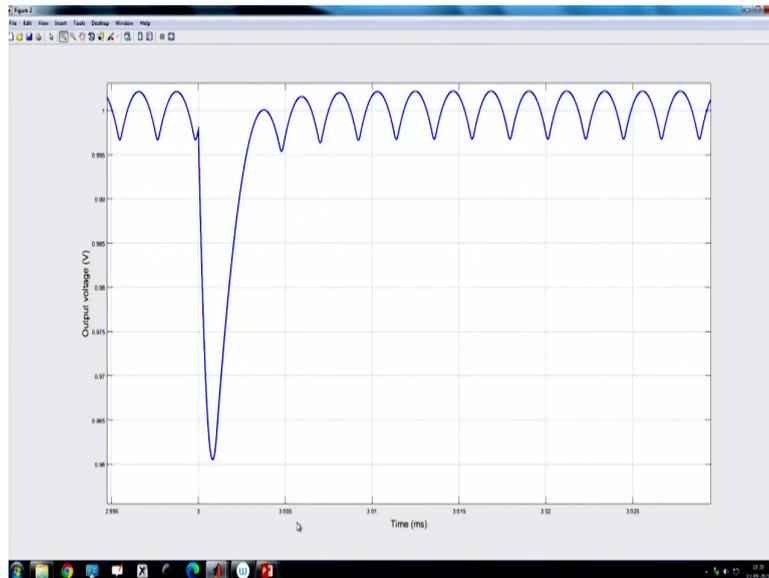
So; that means the integral action if we add; that means, if you go back to the switching surface. So, here, our sigma x I am considering the sigma x is i l minus i 0 plus k p into v 0 minus v ref plus k i into v 0 minus v ref into d t. So, this integral action we are just incorporating and that will act very slowly; so that our steady state error can be eliminated ok.

Alternative way. If we do alternative way using voltage; that means, if you go back to the sliding mode control, using voltage and the derivative of the voltage. Here, so, in the earlier representation earlier realization, we need load current information as well as the inductor current information.

But now, we want to get rid of this load current and output current; that means, sorry load current and the inductor current, we do not need to sense the load current and output current. So, we are taking the error voltage as the one state and the derivative of the error voltage to be the second stage.

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And if you do that, then we can realize this already, we have explained in the sliding mode.

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That we can write x 1 dot x 2 dot realization with the switching control logic. And we have also discussed what should be our switching control logic so that we can achieve we can satisfy the reaching condition and the sliding condition.

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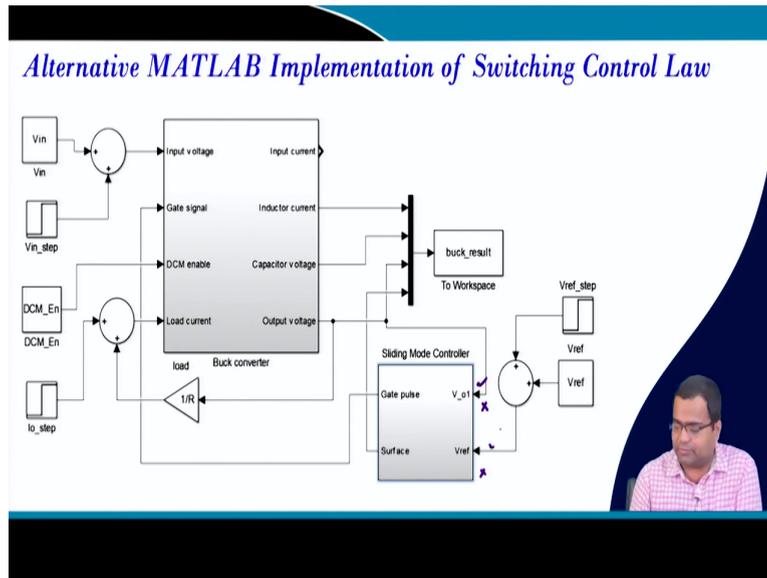
So, the implementation here is different. See, I have not used any inductor current, neither there is any load current. So, it is only output voltage and the reference voltage right.

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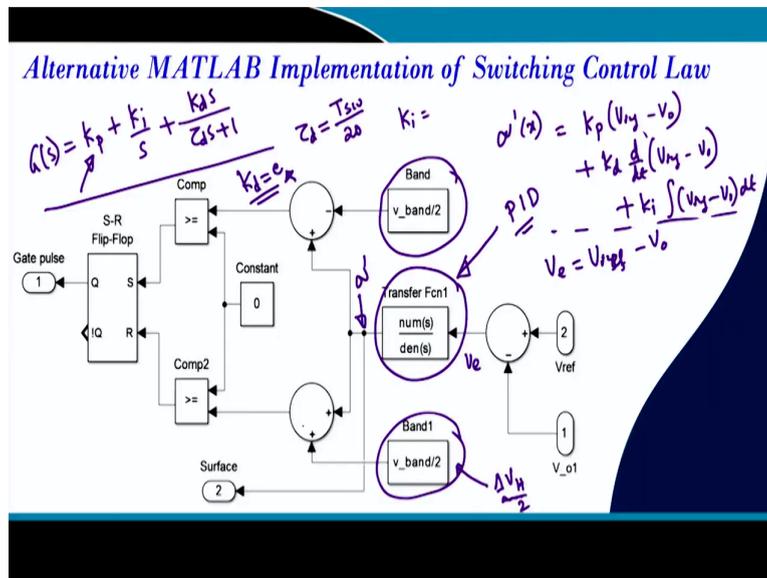
And inside, I am using a voltage band rather than current, because there is no current here. The voltage hysteresis band and here again, I am sitting so; that means, this is like your error voltage where the error voltage is I have taken here v ref minus v 0 and the controller here now, it is something like I am taking like a PID controller.

So, I will tell you that this can be very easily linked with a PID controller. So, where this controller will have three component; that means, you can think of if this is your something like a sigma dash x. So, sigma dash x. I am taking the first state to be my let us say k p into v ref minus v 0. Another state I am taking k d into d d t of v ref minus v 0 plus k i into v ref minus v 0 into d t.

But we should remember, I am not using a direct derivative. I am using a band limited derivative and we have already explained the PID controller right. So, and that will discuss; that means, actually whatever I am considering here, is like a standard PID controller k p plus k i by s plus k d s by tau d s plus 1 PID controller gain ok.

And how to choose this k p k i k d that will discuss, but here I have chosen the time to be very small. I have chosen the switching period by 20, because then we will get close to a derivative action. I have chosen here k derivative to be c, because we want to link this PID controller look like a switching surface.

That we will discuss in the next lecture. And this is my output capacitance output capacitance k i choice is somewhat flexible, but the k p choice is the one which will decide the transient performance. And the selection of this delta v h which is the hysteresis band and this is by 2 here; that will decide our switching ripple; that means, a steady state switching frequency. So, let us go back to our MATLAB and see what happen. If I go to our voltage base controller.

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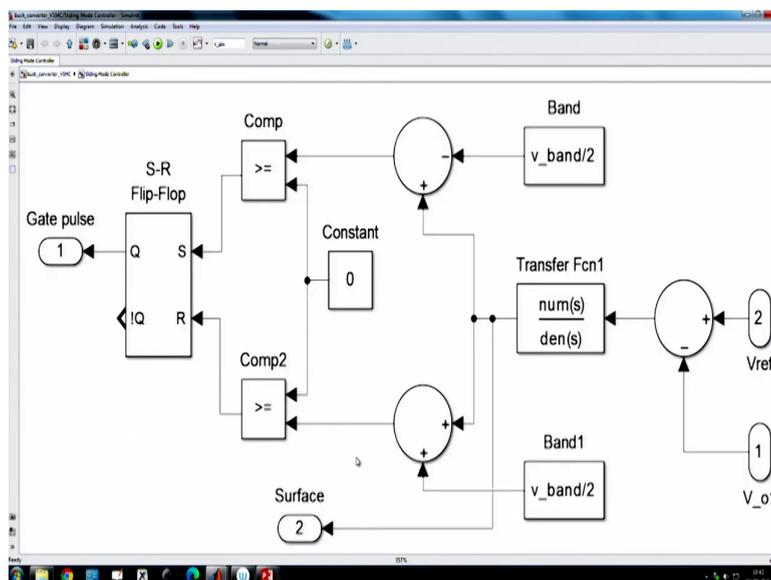
So, this is my voltage base control, which I have explained here, v band.

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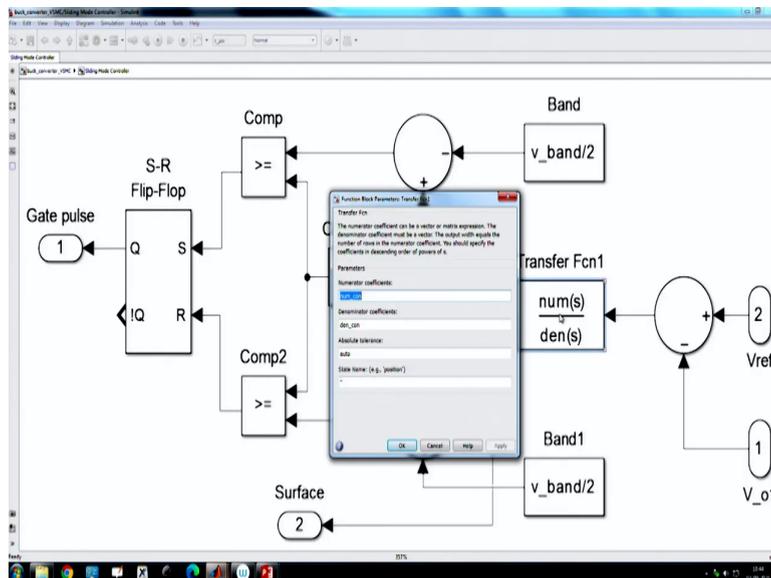
And this is a transfer function that we are defining from inside. Here, we have already discussed that we have not used any you know voltage or current load current, neither load current nor inductor current.

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Now, we want to set this logic. This was the logic of our PID controller. So, here we want to consider. So, we want to stop here this part comment here ok. So, you can see the derivative

gain. I said it is a capacitor voltage. So, it is t d by 10. So, you can take t d by 20 there is no problem. And then, numerator and denominator I have set. Let us see what happens.

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In a simulation file, I have to change the VSM, because this file name is V ok. So, the band voltage band I have set one hysteresis, because of achieving the desired value. So, let us see what happens.

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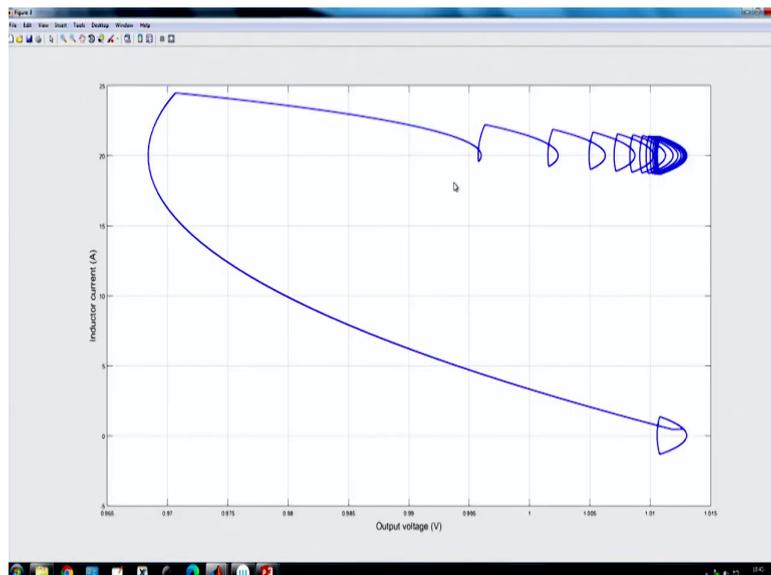
So, this is my voltage base realization. There is no current realization here, but you can see, it is taking more cycles to reach steady state.

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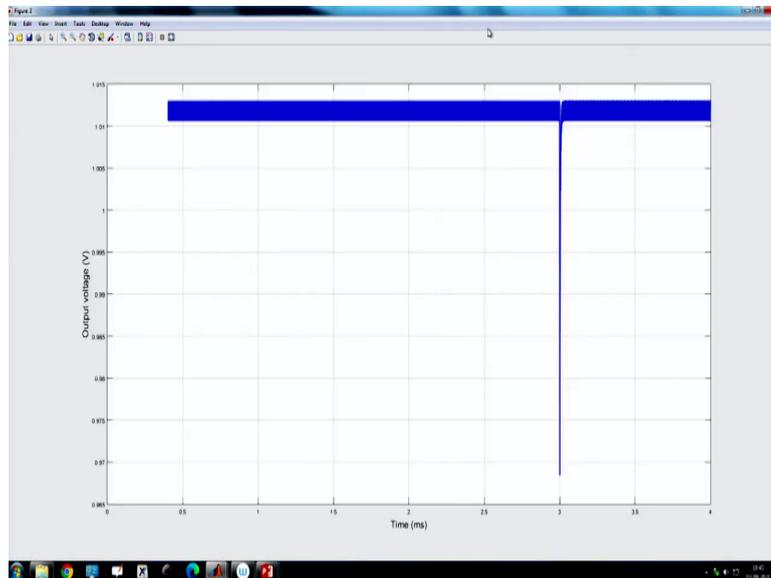
That means, it is not optimized or it is not the optimal performance.

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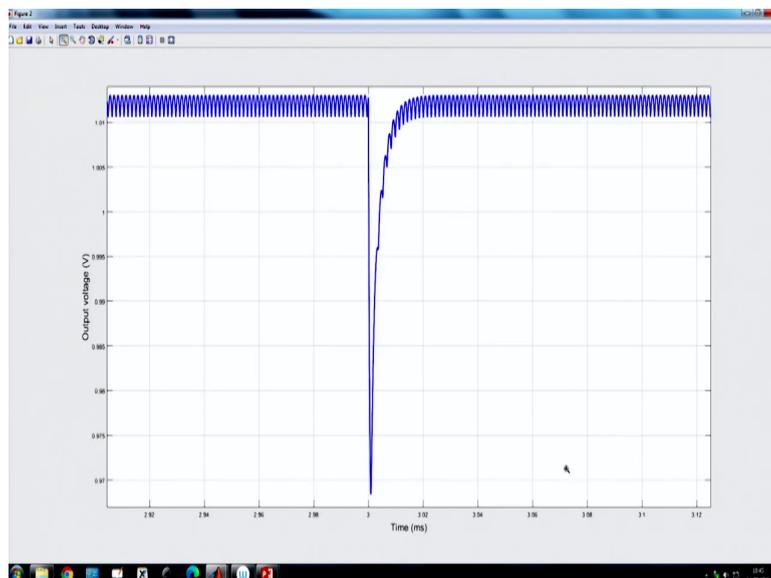
So, you need to increase, but there is also steady state error. So, first let us see what should be our K p.

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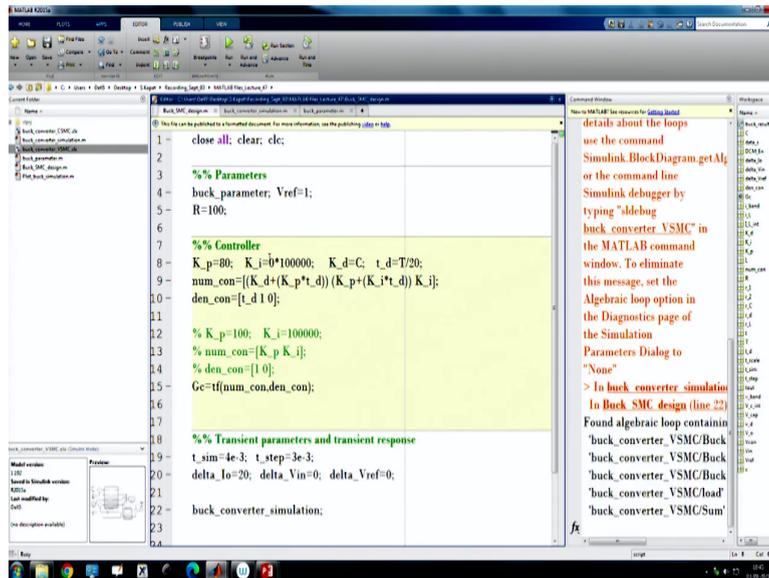
So, if I set K p to be 80 for example.

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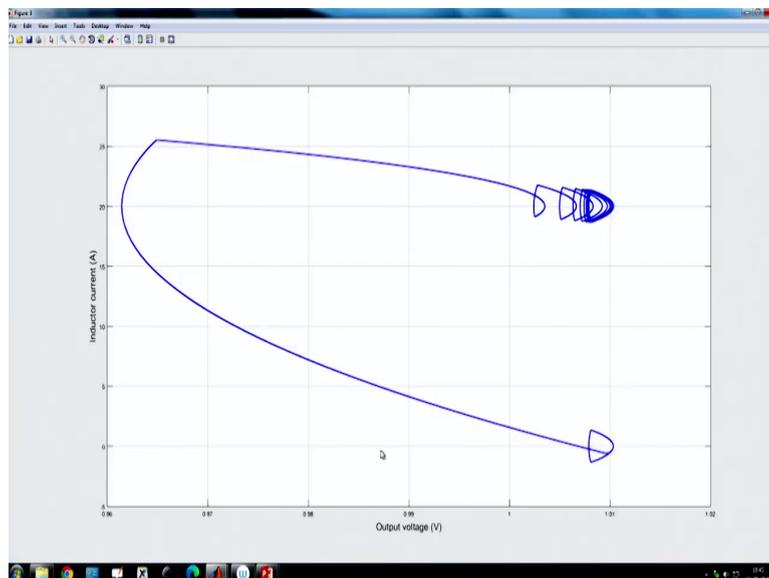
Then, we will see that we are getting near to optimality condition.

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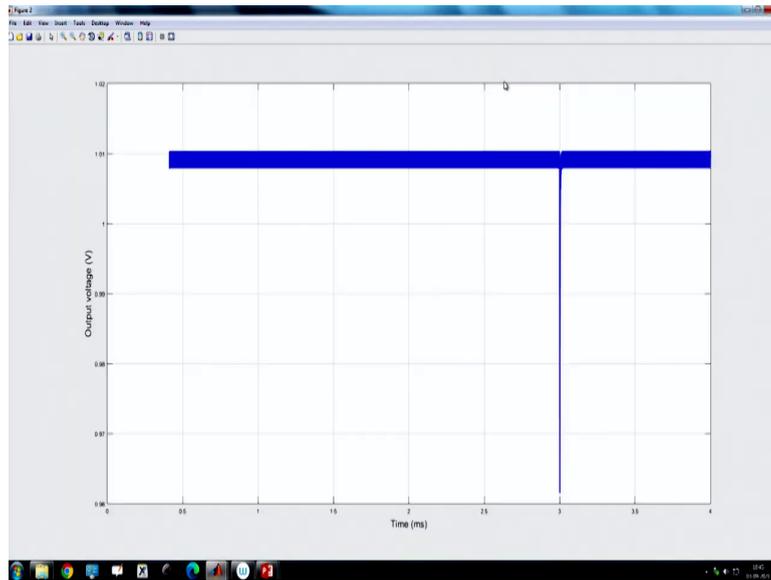
But still, it is not exactly coming to the optimal.

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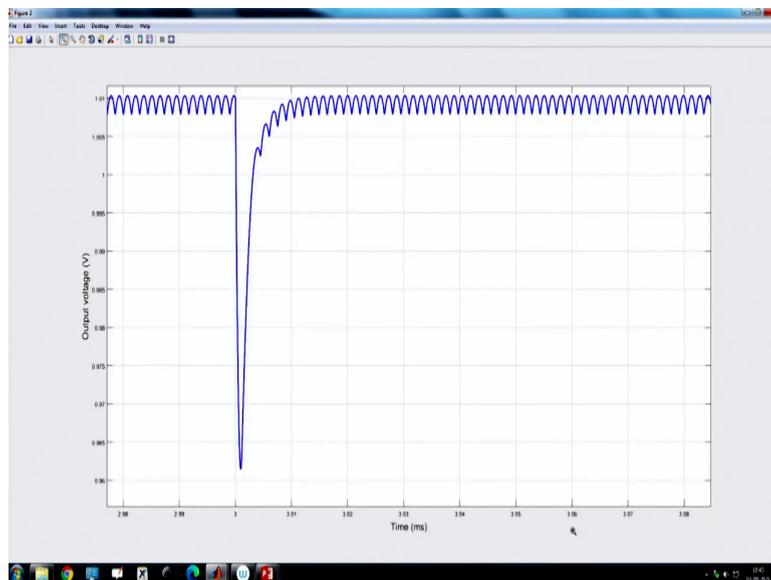
That means; you know it is still slightly over them.

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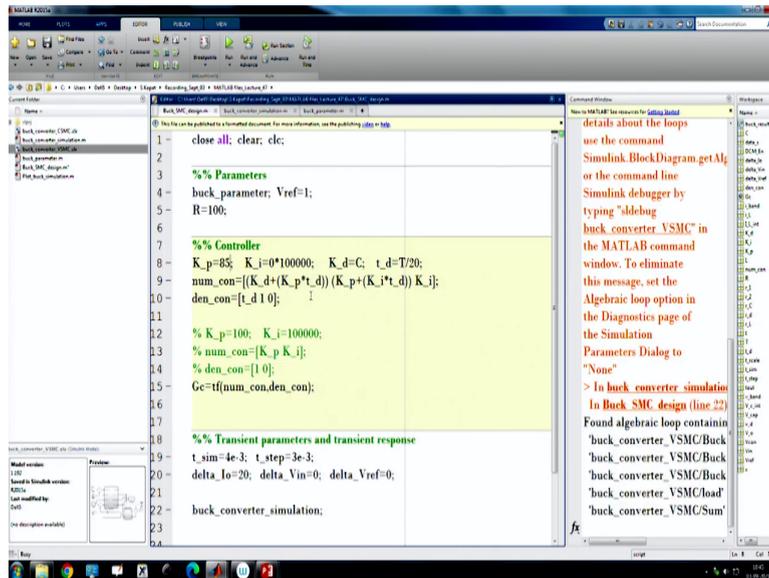
So, we can further increase the gain; let us say 85.

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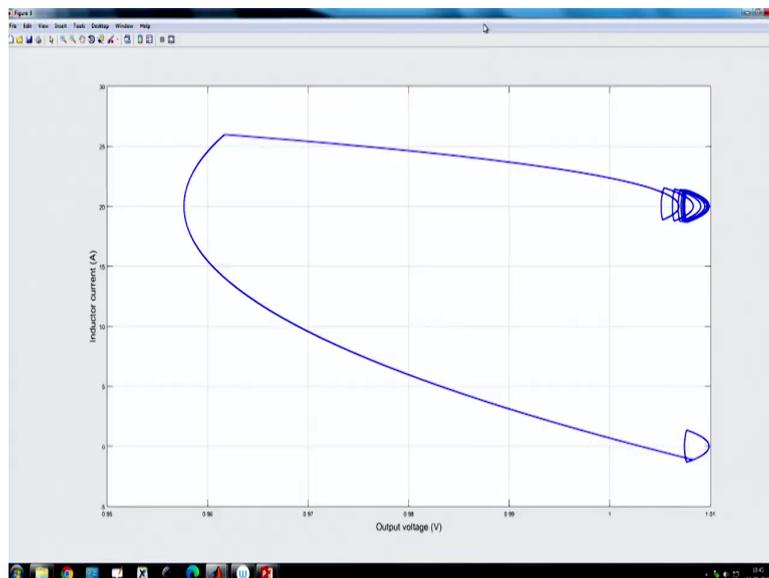
And you will see that it is almost coming to steady state. But there is a steady state error, because it is shifted by almost 10 millivolt and we need to if you want to eliminate, let us enable the integral action.

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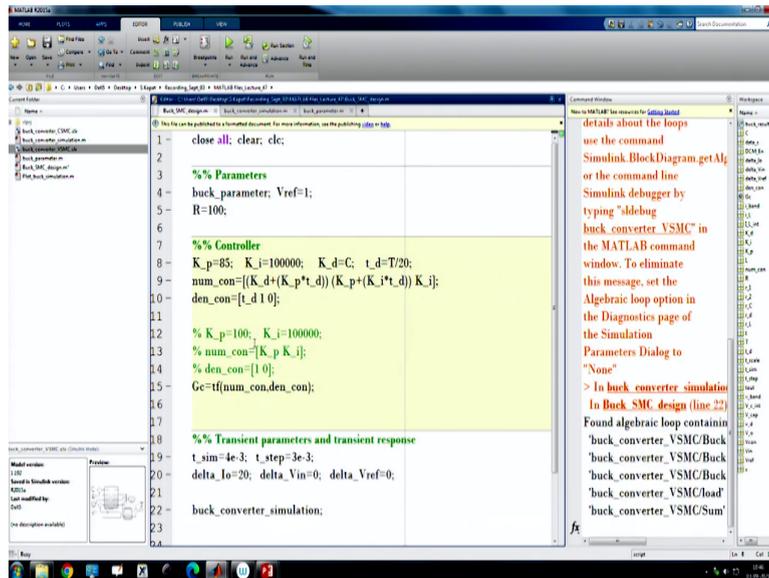
So, then it will make sure that there is no almost steady state error ok.

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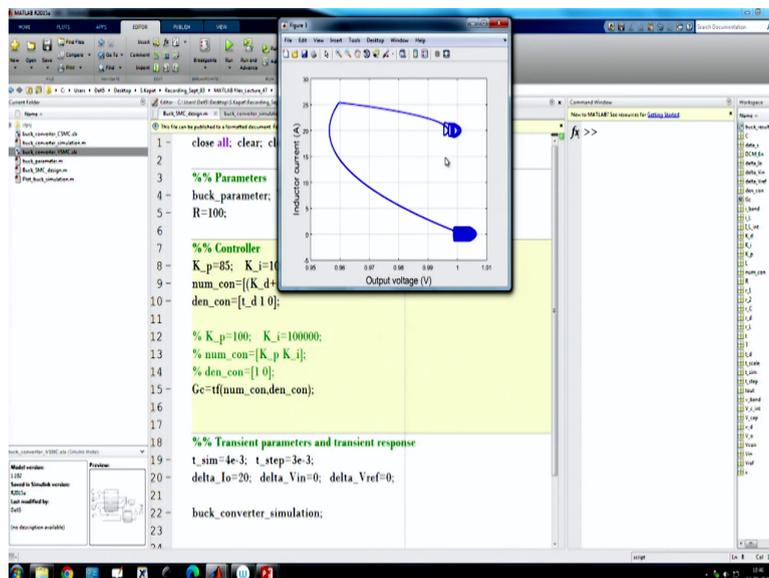
So, we have enabled the steady state error.

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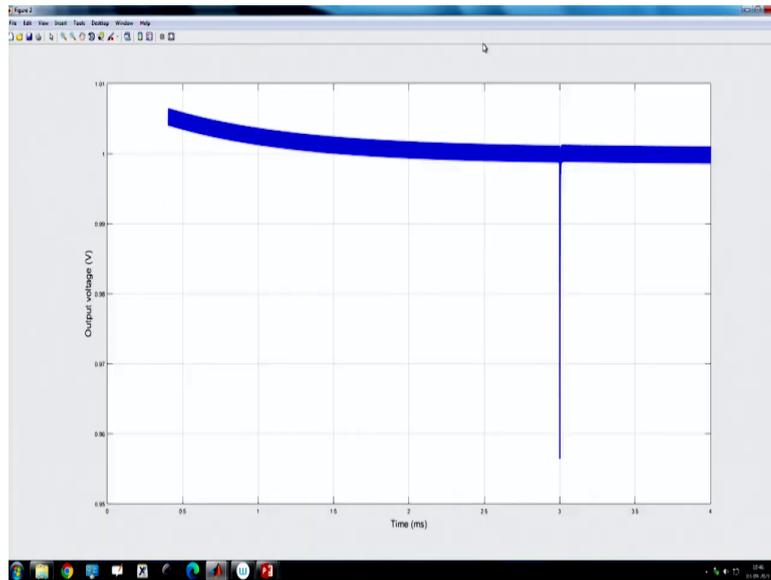
Now so, it is coming back.
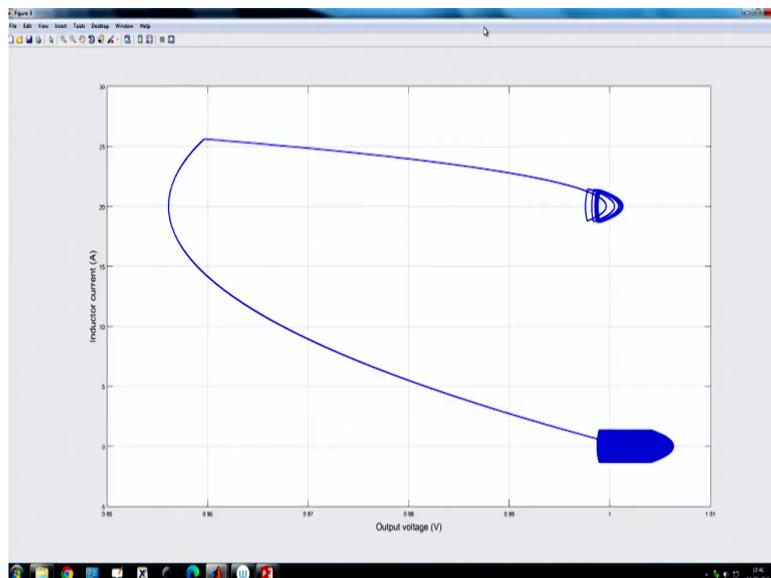
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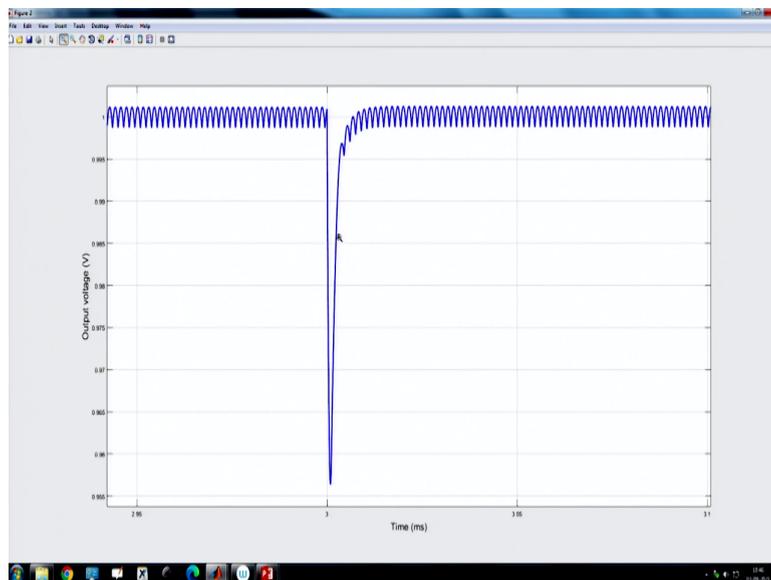
And you know we are coming close. So, we can further increase.
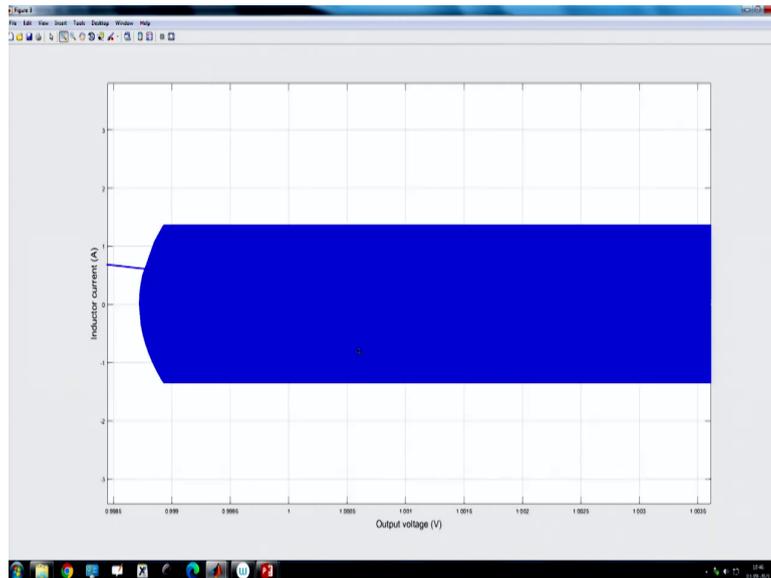
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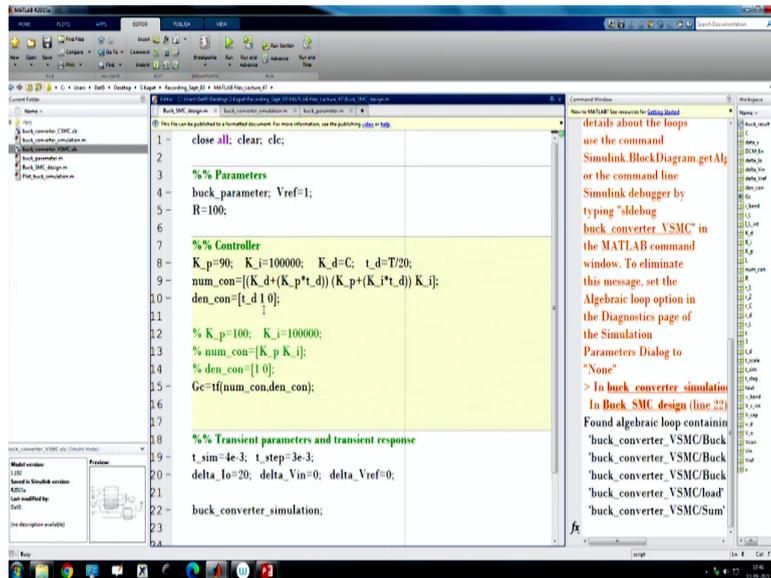
Because so, we can do like 90.
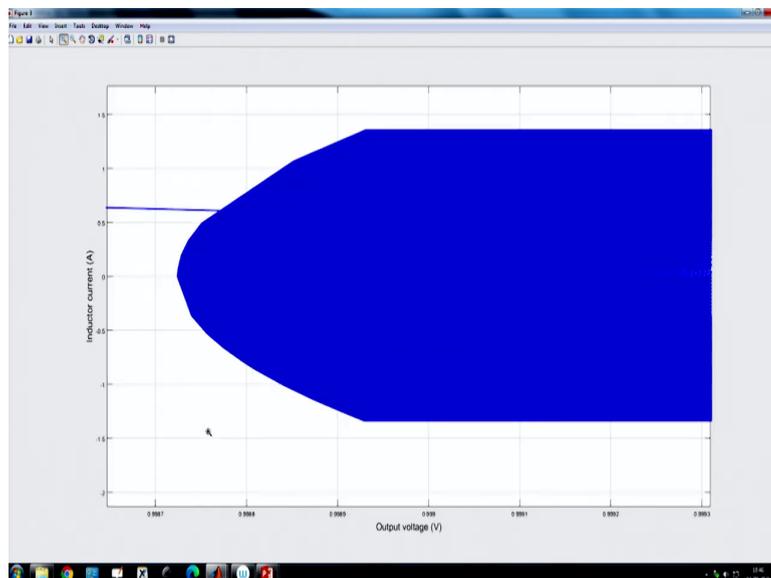
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So, because it is taking here.
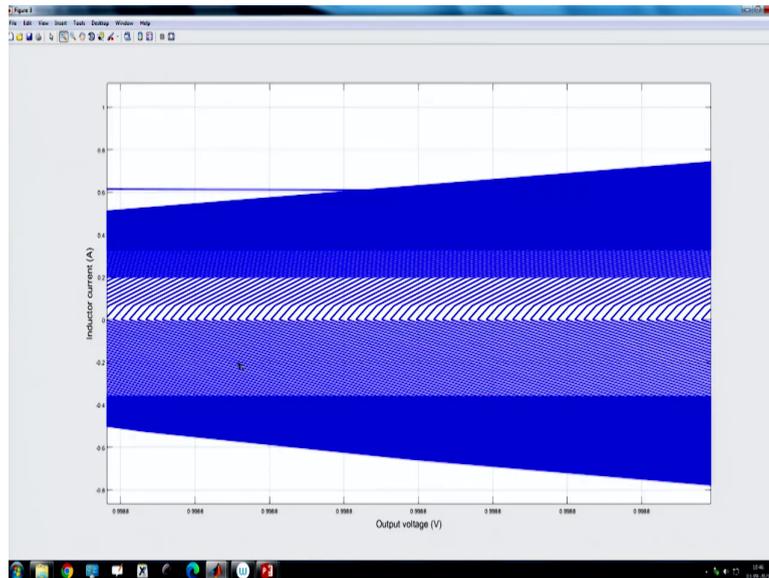
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Because of the integral action. It is slowly approaching.

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And finally, it is the reaching steady state.

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So, more number of cycle. So, you can eliminate some of the data here you know.
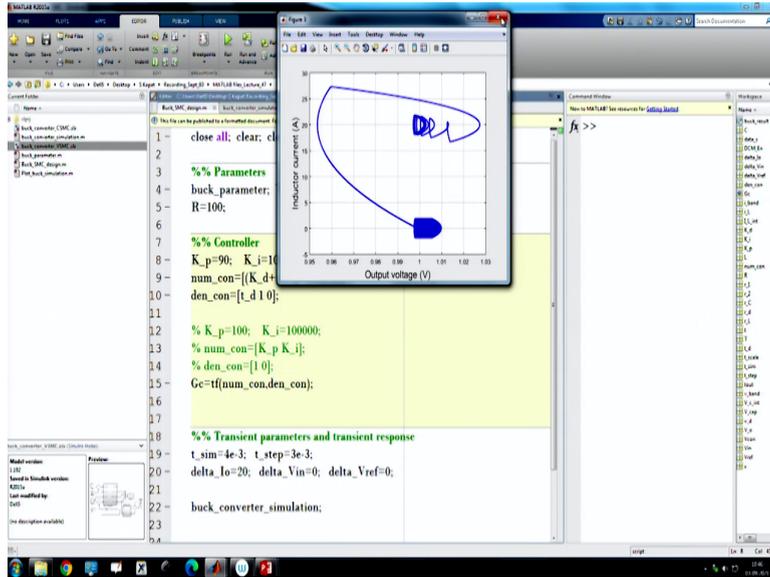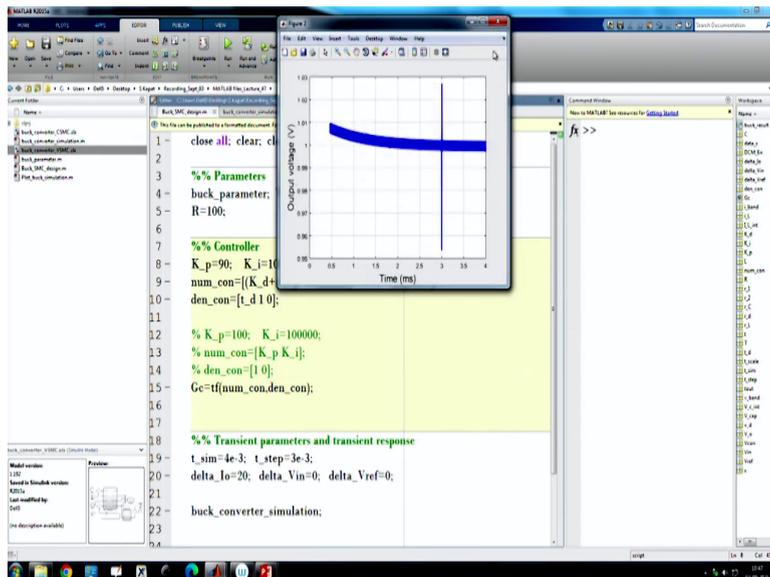
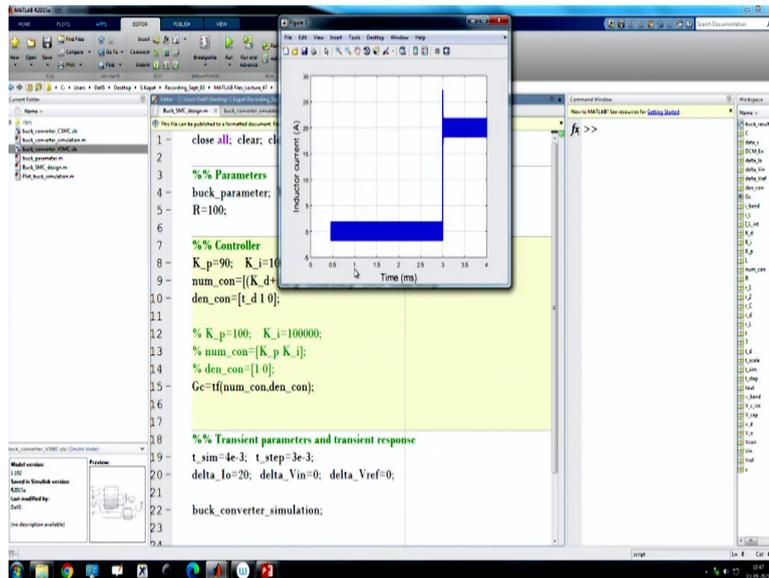(Refer Slide Time: 58:42)

Or if you make it 10.

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See, the derivative also has a role that a time constant.

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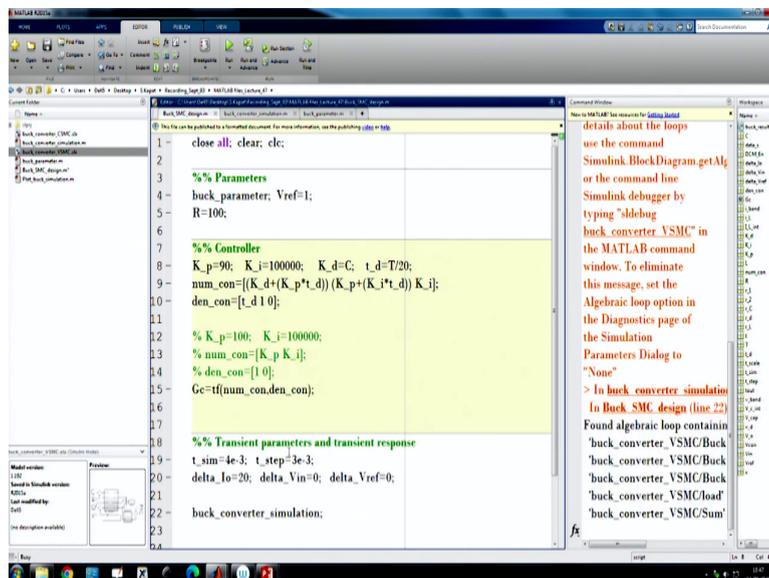
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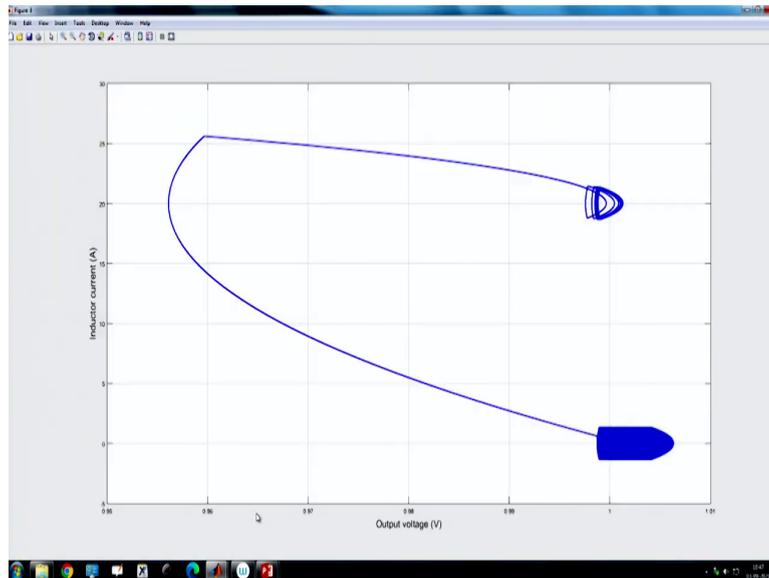
So, if you limit the band of the derivative that also leads to so; that means, the derivative filter time constant also plays a significant role.

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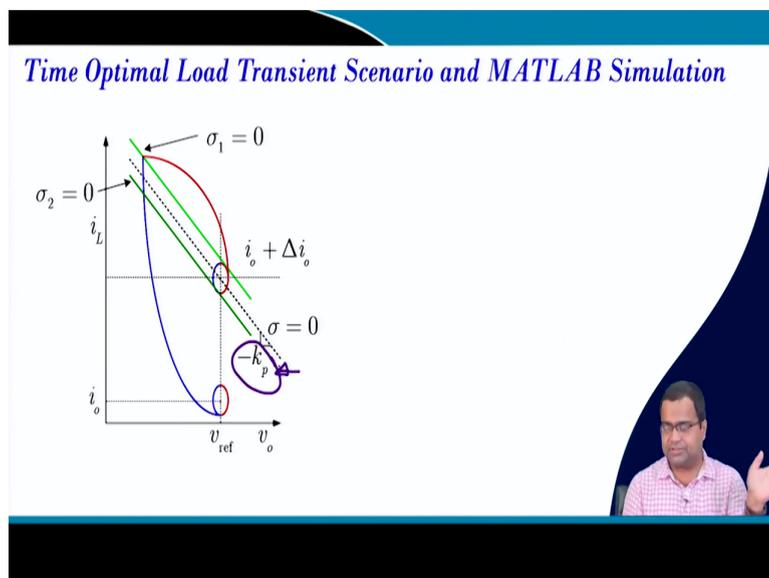
So, this part we will discuss. So, the optimal transient scenario and the MATLAB case study we have shown that close to optimal the choice is very the proportional gain is very important. This play a significant role in the shaping the transient response.

Now, second order switching surface, because here we have taken first order switching surface, but first order switching surface we need to optimize k p o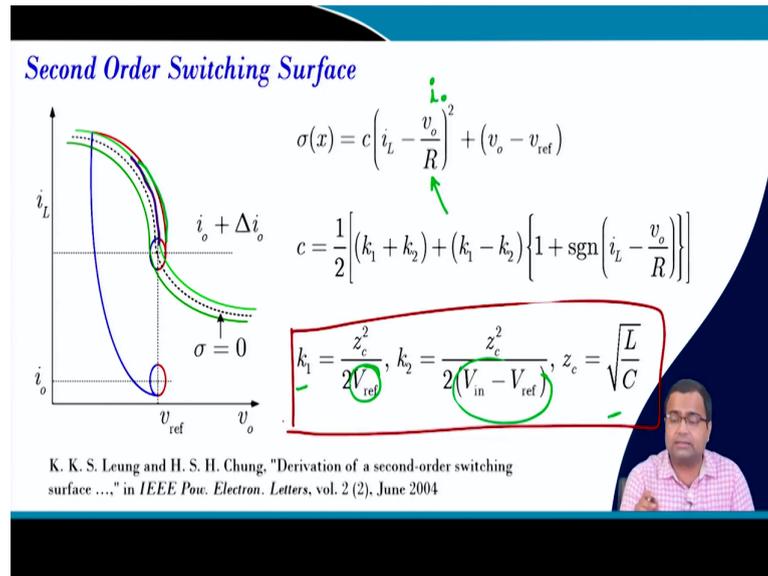therwise you will end up with either under you know I will say under damp behaviour or. Sorry overdamped behaviour or there can be high overshoot undershoot.

So, the choice of k p is something which is we need to take care; otherwise, this may not be a good solution in terms of optimal response. And that is one of the objective in this course that if you frame it into a PID control and if you can derive this optimal gain, then first order switching surface is sufficient. But if we consider a second order switching surface, the boundary control where we want to take the desired switching surface. Sorry switching surface, which is almost taking the shape of the off state trajectory.

That means the term boundary control comes if we set the switching surface close to the boundary of the trajectory or basically the desired trajectory. Then we can get optimal response right. So, here the second order switching surface is better in compared to the first order, which takes somewhat closer to the desired trajectory. Because you can see the green one is the parallel line to the actual dotted line, the second order surface and the red one is my off state trajectory.

So; that means, my red one is the off state trajectory, though they are not exactly equal. So, I am talking about this green one and I am talking about you know this one. So, they are actually away, they are slightly different, but it is far better than first order. So, then it was

proposed that if we take the second order switching surface, then you can achieve close to time optimal performance without much changing of the parameter by only considering by changing input voltage output voltage scenario we can achieve close to optimal performance.

And here also you need to incorporate the load current because for resistive load. This is my load current for resistive load. It is v v 0 by R for current load. It is i 0 right. So, this is second order switching surface can achieve close to optimal performance. So, here also we need to sense the load current ok.

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So, now higher order switching surface, so second order switching surface can go close to optimal performance for a given parameter which depends on the input output voltages and characteristic impedance, and this is generally set from the design ok, but the implementation require load current for this case. Second order switching surface then the raster switching surface, which in this paper you know it is compared the performance using different switching function.

That means first order, higher order and then it has proposed the switching surface which is computationally effective and can achieve close to optimal behaviour. The other one is a natural switching behaviour where you know if we because our desired one we want to achieve the target trajectory and that can be achieved by if we normalize the state variable with respect to its operating point, and if you do that then you can achieve perfect time optimal control.

But the implementation may be slightly difficult because you need to you know normalize the parameter, but these techniques are also very effective. So, all these techniques higher order, natural switching surface can lead to time optimal performance for arbitrary transient you know all these scenarios. So, the many other switching surfaces exist which can achieve very fast transient response.

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Now, the choice of switching surface the first order surface we saw it is a simplest to implement, but it requires slope optimization or basically the optimization of the k p that is acts as a question ok, but it is very simple to implement. So, in high frequency application this technique may be useful, because it is it resembles something like a PID control and that we are going to discuss more in detail.

The second order switching surface or the higher order, it requires more resources because you need to create a square block you know and you need to incorporate many other. If you go back these parameters you have to plug in this parameter. This is useful, but in terms of resource wise this can consume more resources and also it needs to sense the load current right requirement. Natural switching surface is also a very effective technique, but again it requires normalization and it may be require most resources.

So, these techniques may be useful when you are talking about a few hundreds of kilohertz switching converter maybe for high power. But when you are going for megahertz switching

frequency or maybe 500 kHz or more, then you need to optimize or particularly when you are going for power management i c, where the resource plays a significant role.

So, our choice the question is that is it possible to achieve the fastest response using a first order surface only? If we can do that, it is the simplest one and structurally similar to k p k i k d PID controller. These are often used in any high frequency p m i c or d c d c converter. So, we need to take the advantage of that existing PID controller and we need to frame that PID controller into a switching structure first order.

And then we have to calculate the gain and we need to find out how this gain can be optimally tuned by incorporating the switching function. So, we need to link the PID control technique with a PWM control and PID controller linking with you know I will say the switching surface; the linking with the switching surface. We need to link with the switching surface. So, this is the link that we are going to see.

If we can do that, the first order switching surface link with this PID controller and link with the PWM control then our traditional PWM control, whether it is a current mode or voltage mode can be tuned to achieve the fastest time optimal response by formulating using a first order switching surface or something similar.

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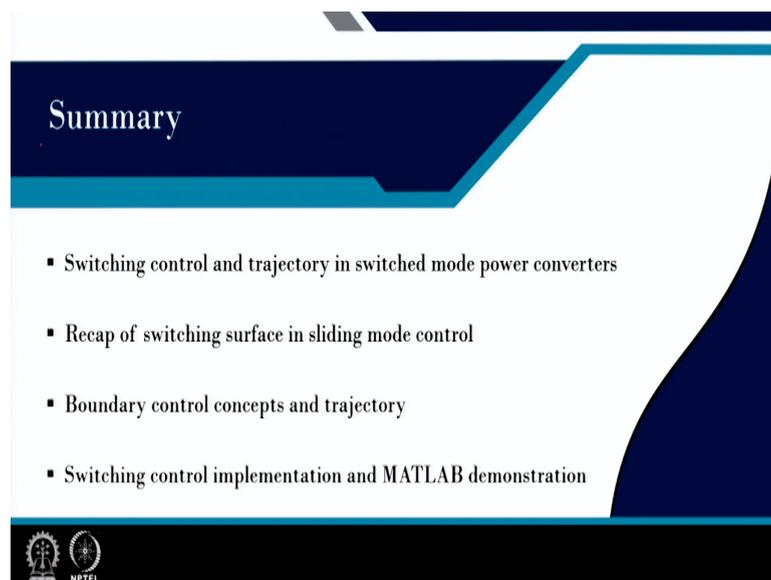
So, in summary, we have discussed switching control and trajectory in switch mode power converter. We have discussed the switching surface in sliding mode control. We have

discussed a boundary control concepts and trajectory and we have also discussed in sliding mode control. Actually, the boundary control is a subset of sliding mode control where we want to design the surface in order to make the surface look like a target trajectory.

But by doing that, we are going for higher order switching surface and that surface can be more intensive in terms of resource requirement and in terms of complexity. So, our target is to make the design simple and achieve something optimal and use the PID controller structure we want to exploit, and we have also discussed a few MATLAB case studies. So, with this I want to finish it here.

Thank you very much.