Control and Tuning Methods in Switched Mode Power Converters
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Module - 08
Small-signal Design of Current Mode Control
Lecture - 37
Accurate Small-signal Modelling Under CMC and Verification Using MATLAB

Welcome back, this is lecture number 37. In this lecture, we are going to talk about accurate small-signal model modelling under current mode control and verification using MATLAB.

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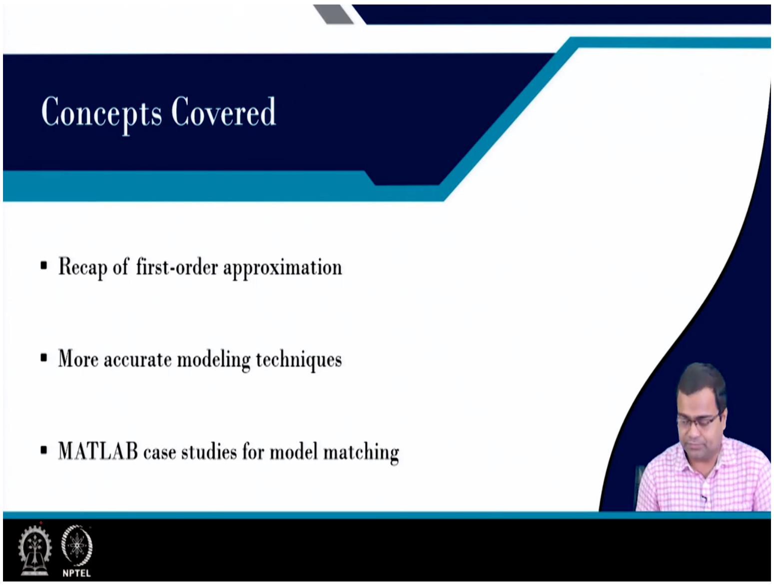

So, in one of the previous lecture we started with the first-order model; that means, the impedance analysis with closed current loop right. So, we took current mode control and use a very basic first-order model right and we derived the equivalent circuit and then we sorry we obtain the equivalent circuit and then derive the various transfer functions.

So, today in this lecture we want to first recap that what we learn in the first-order approximate model. Then we want to come up with a more accurate model, what are the other modelling technique what are the sources of inaccuracy and how can you improve it and then finally, we want to show some MATLAB case study with some model matching ok under current mode control.

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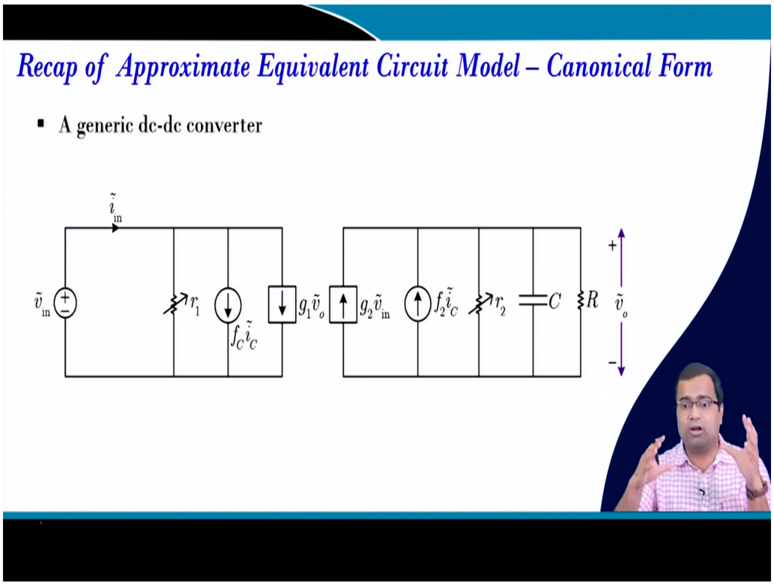

So, recap I mean we want to approximate equivalent circuit model in canonical form. In a generic DC-DC converter, this model we have already obtained and this model is well known.

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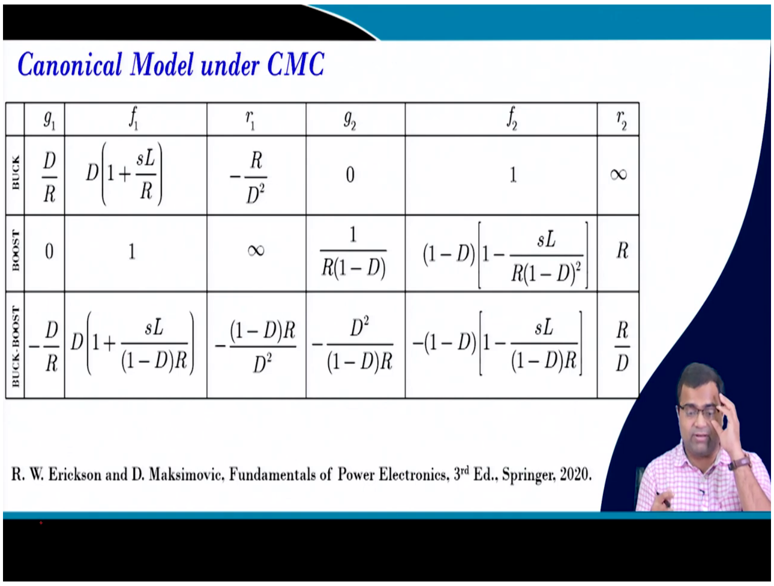

And, you know it is this model all these parameters are available in Fundamental of Power Electronics book.

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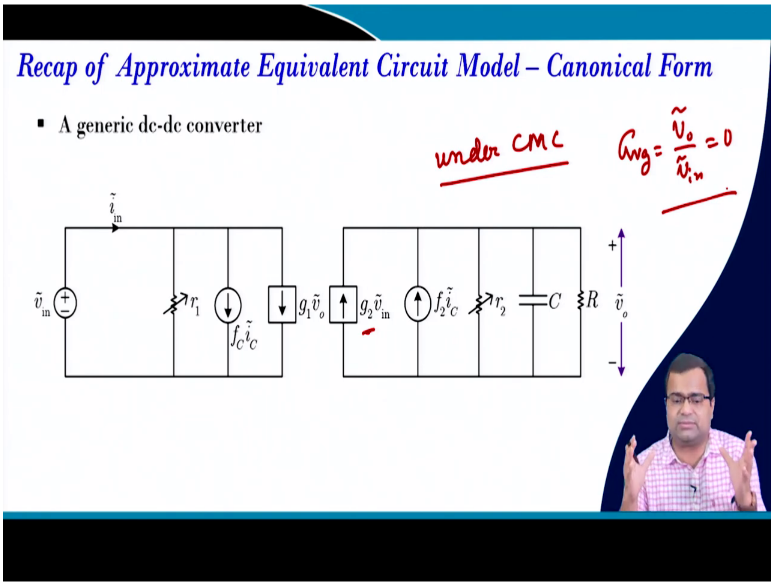

And if you go back to the previous diagram. So, from here we can find out audio susceptibility output impedance control to output transfer function various transfer functions under current mode control, but these are all under current mode control ok. Now, you will find this g of 2 is 0 and if you go back, this g of 2 is linked with input voltage; that means, we will see for a buck converter this approximate model.

If you try to derive audio susceptibility G vg right, which is v 0 by v in it will be simply 0 in this case because g t equal to 0. This indicates that there is no effect in the output voltage for a change in supply voltage, but it will not be the case for a boost converter there will be a first-order effect.

But here we are only talking about buck converter model matching because we have a separate lecture for boost converter model matching and current mode control design. So, that means, audio susceptibility 0 means this is something which is very much approximation, but we need to figure out otherwise this model first-order is quite nice, very simple and we want to check whether this model how far it is valid.

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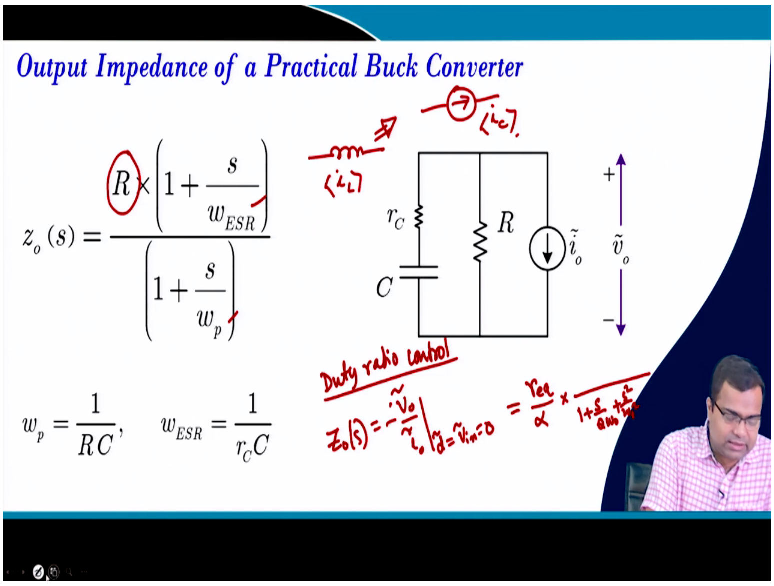

So, output impedance of the practical bug converter that we derive, so, it was R ESR because this is under current mode control. When we convert it this inductor current into a control current source right, we converted into a control current source because we have assumed that average inductor current can be replaced by average capacity average peak current and we are directly controlling the peak current by which the inductor becomes a control current source.

So, this is the assumption since the inductor becomes a control current source, the inductor current dynamics is not coming into picture and for the output impedance, we ignore the change in control perturbation in the control signal; that means we are keeping using a fixed current difference, but the inner loop is closed. Remember that the inner loop is closed. So, this is our expression with the load resistance for a buck converter, one ESR 0 and one pole.

Now, if you see this output impedance under you know duty ratio control, what we found under duty ratio control? For duty ratio control; that means, what was our output impedance when you know we are talking about minus v 0 by i 0 hat with d perturbation v in perturbation equal to 0. We found that in practical there is a r equivalent by alpha multiplied by there are two 0 the polynomial is 1 by s Q omega 0 plus s square by omega 0 square we found ok. So, let us let me write. You know we need some space. So, I will write it here.

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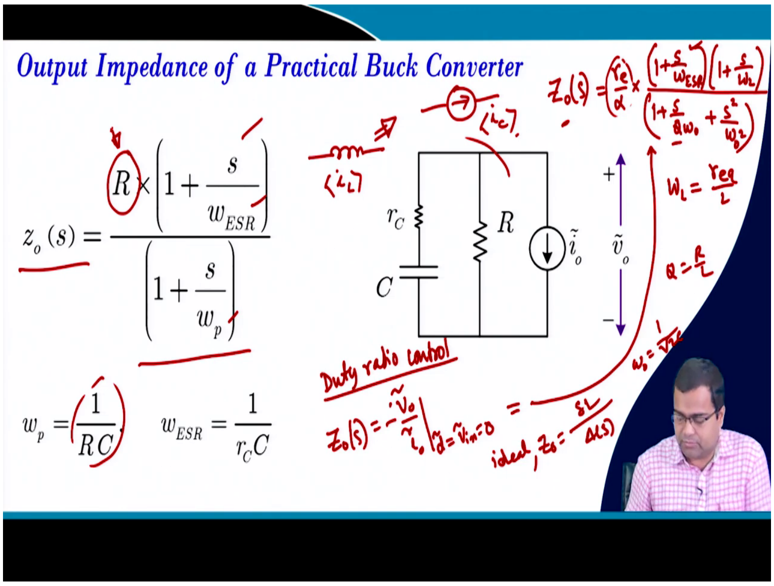

So, that means, output impedance we found r e by alpha into 1 plus s by Q omega 0 plus s square by omega 0 square and two 0s we got one 1 plus s by ESR and 1 by s by omega L and what was omega L? It was r e equivalent by L and r equivalent we know it is r l plus r d s 1.

So, in duty ratio control, the common thing you will find this is coming into picture; that means, for an ideal buck converter, the output impedance this term will not be there ok and this term will not be there. So, output impedance will have only R L c circuit; that means, there is no parasitic component. So, ideal case for ideal case if you write you know even if you apply limit you know that this coefficient r e tends to 0 and other term.

So, ideal case output impedance can be written as the delta s remains same. It will be simply s f. So, here only omega 0 is it will be in this case omega 0 will be 1 by square root of L c and Q is simply R by L. So, these things are known, but when you close the current loop, then the output impedance is the different drastically different your ESR 0 is there, but pole is become a single pole like a first-order and pole is a function of 1 by RC.

Because this branch looks like RC circuit, but what is the problem? The output impedance you see it is DC value is a load resistance dependent; that means, the output impedance with closed current loop under DC behave like a resistance. So, that means, if there is any load step chain, the output voltage will immediately change by the load step multiplied by the r and the negative value right. So, which is not desirable. So, that is why the current mode control suffers for poor load regulation because of high output impedance for closed current loop ok.

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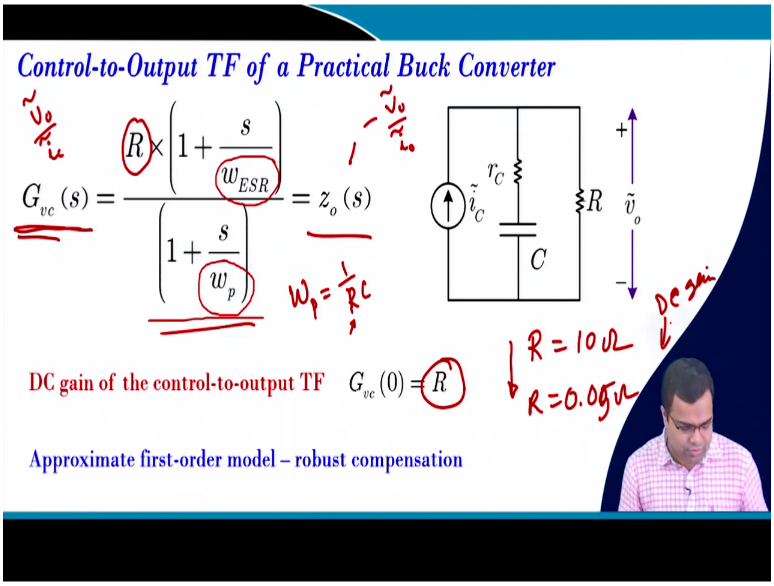

Now, if you take a practical buck converter control to output transfer function. So, it is same as the output impedance only earlier it was an external sink load now that is replaced by a source side control current source that is it so; that means, here it will be v 0 by i c by taking other thing constant and here it is minus v 0 by i 0.

So, one way the load current is sync current and here the control current is a source current so, same branch. As I said that in this case, if you get the DC gain that s equal to 0 it is totally load dependent; that means, even if you want to design a closed loop control, this control to output transformation is a part of the loop transfer function and the loop transfer function gain DC gain becomes load resistance dependent.

And if there is any change in load resistance and which is about to happen, then you have a severe problem with a DC gain problem ok, but this approximate model is very useful in terms of robust compensation because there is no double pole anymore. So, there by virtue of close inner loop one pole become much faster and which is the inductor pole which goes very far in the left-hand side because inductor becomes a control current source. So, we are almost taking that inductor behaves immediately.

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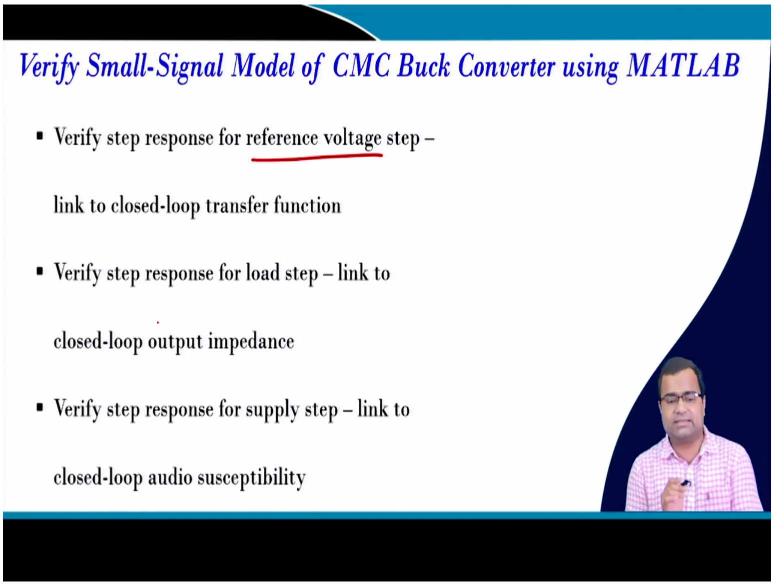

Now, we want to verify thus this small-signal model current mode control with actual switch simulation how far it works under total loop. So, first we want to do reference step transient, then closed loop output impedance, a stabilized transient and we want to link audio susceptible. These three we want to do, right.

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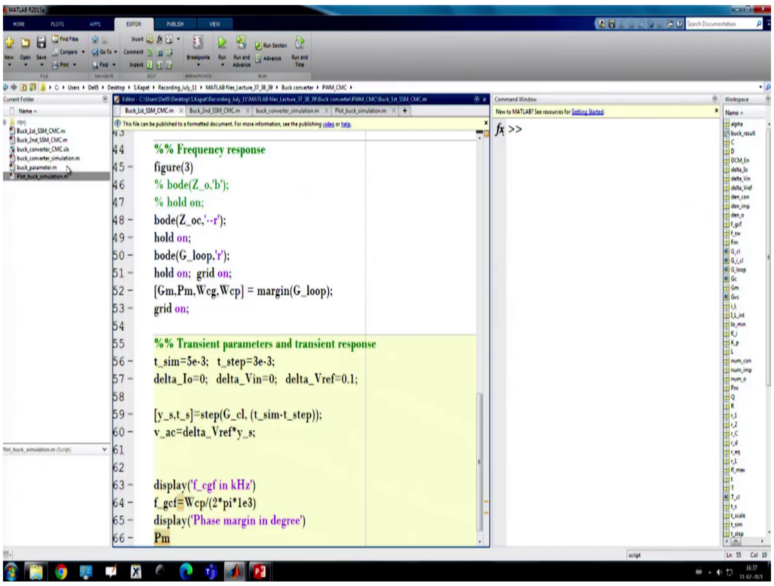

So, we already have MATLAB code.

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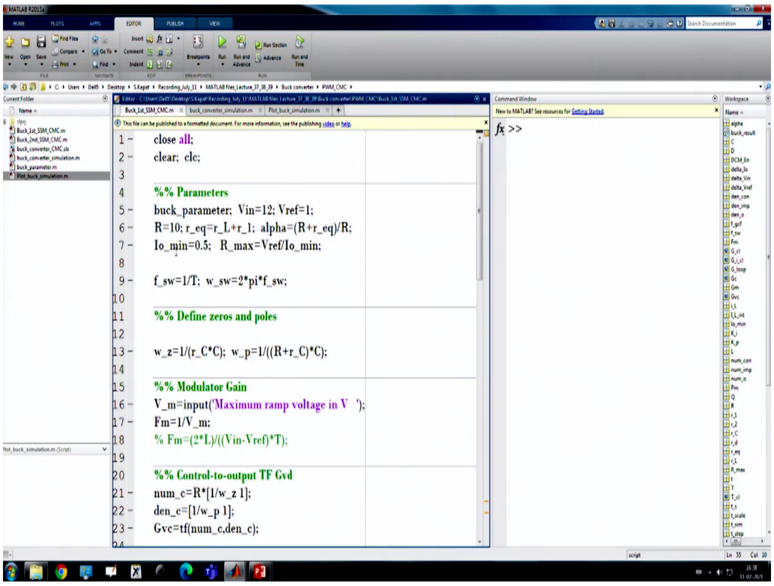

So, let us go back. So, we are talking about this is the first-order model and if you see the first-order model, this is the parameter file that we call load resistance, then this is our esr 0 and this is a single pole; that means, if you take if you try to map correlate. So, this is our single pole omega p and I take omega z to be ESR 0 ok ESR 0 ok ESR 0.

Then what is the control to output transfer function? It is R times 1 plus s by w ESR and denominator is 1 plus you know because in control in you know transfer function we write the s polynomial coefficient first and then constant term, right. So, this is my control to output transfer function.

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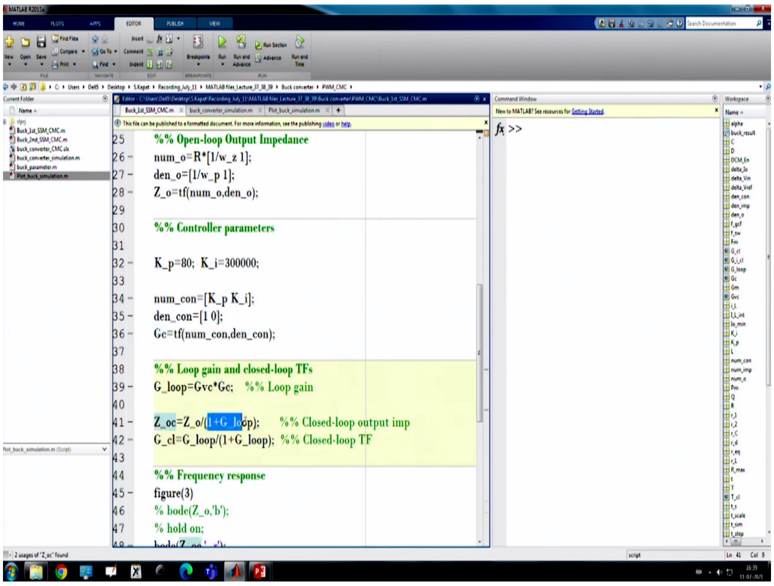

So, it is very simple. The output impedance open loop is same as the control to output transfer function, but I am writing again. Then I have set some arbitrary value of PI controller because it is a first-order system and you will see in the next lecture a PI controller or a type 2 compensator should be sufficient and I have taken a PI controller K p 80 and third you know it is like a 300,000 is my K i ok. So, K p K i is just a PI controller.

Then the closed loop gain which is our loop gain, is a product of the control to output transfer function multiplied by your controller. Then what is the closed loop output impedance? It is nothing, but open loop output input is divided by 1 plus loop transfer function, the closed loop transfer function is loop transfer function divided by 1 plus loop transfer function.

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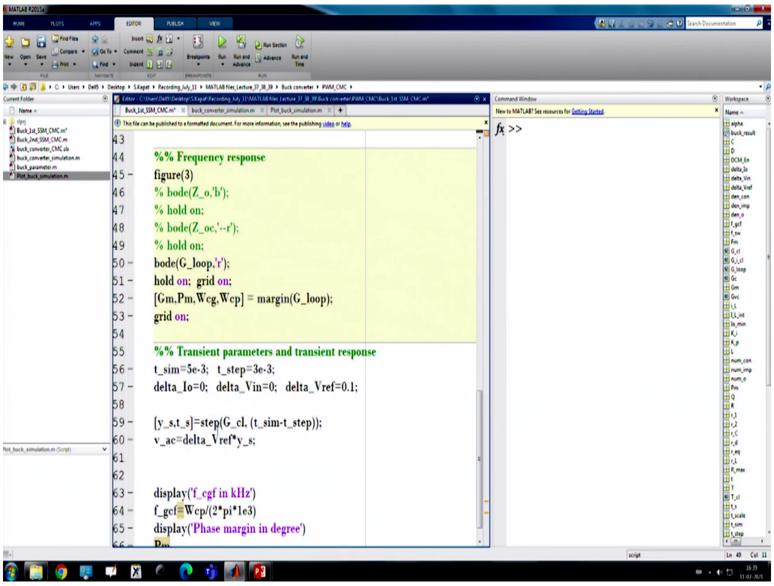

And, here we have all the Bode plot. So, once we loop transfer function and we can find out the gain margin, phase margin, you know bandwidth and crossover frequency and all. So, initially we want to carry out a reference voltage transient because what is our initial target reference voltage time, this will give us the bandwidth concept ok.

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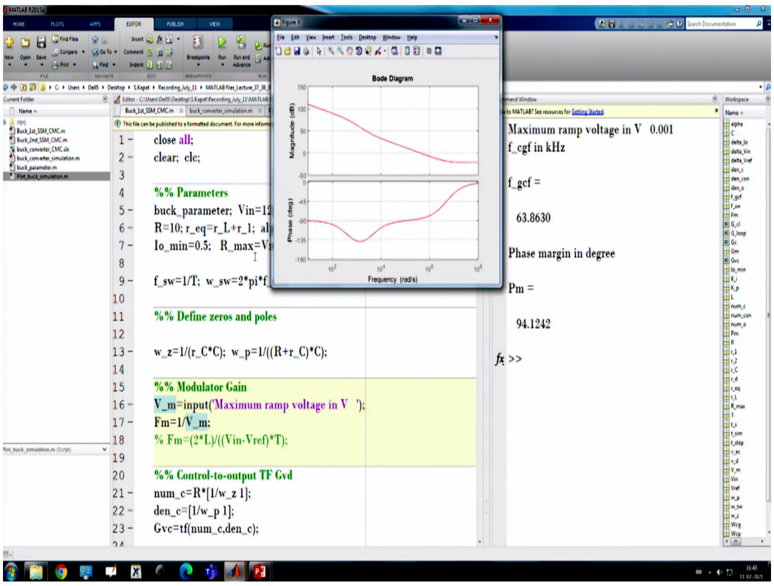

So, then we want to match the model ok just a minute. So, for you know we are using a very small ramp compensation very very small it is almost negligible ok.

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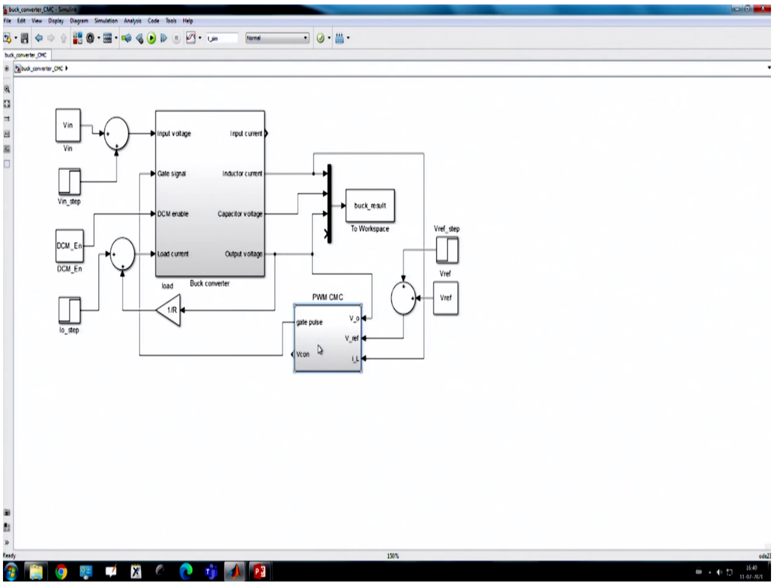

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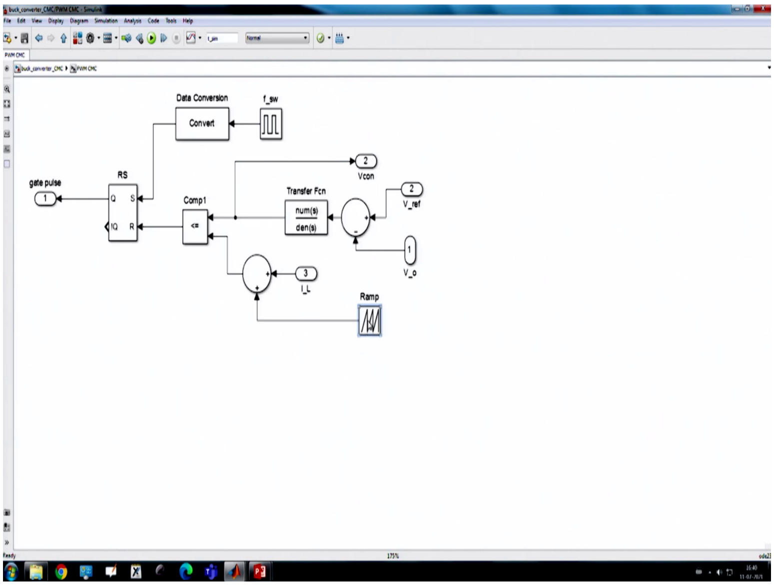

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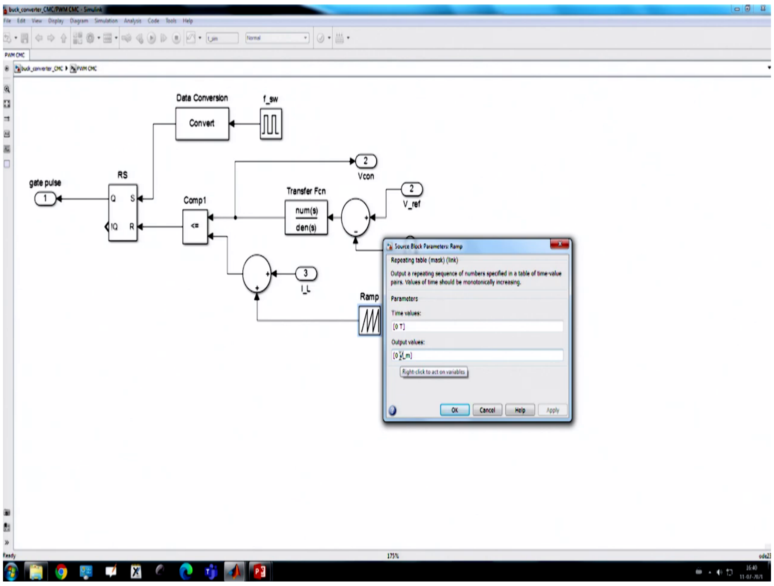

And if you go back to the current mode controller block, I am using a very small compensating ramp V m which I am setting 0.001; that means, it is 1 millivolt which is negligible; that means, as if we are not using at all. Then if I go back so, you got phase margin 94 degree which is like very much over damped system.

But gain crossover frequency to be very high, 63.86 whereas, 500 kilohertz is my switching frequency. So, it is roughly one 8 of the switching frequency; that means we are going even further. You know we are increasing the bandwidth or crossover frequency compared to voltage mode control.

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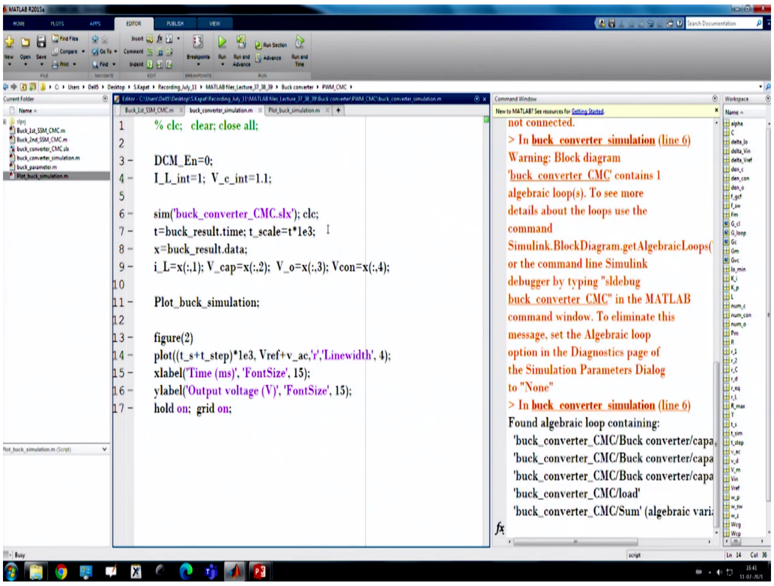

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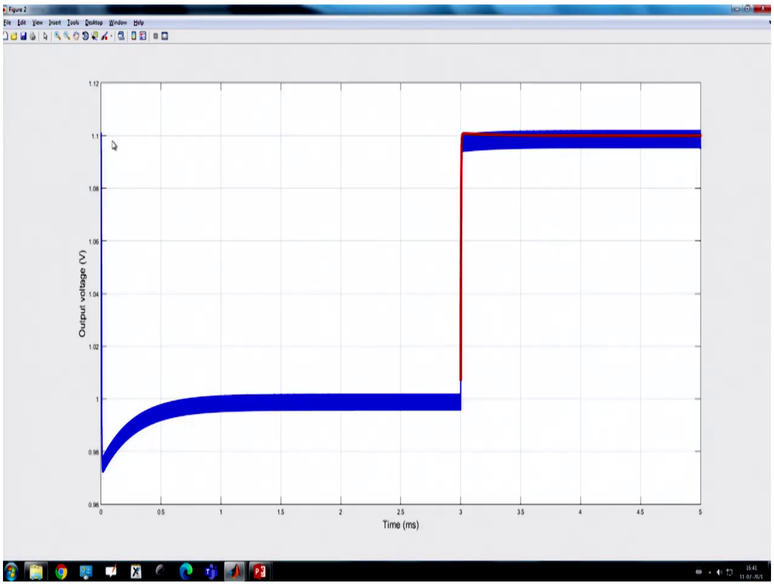

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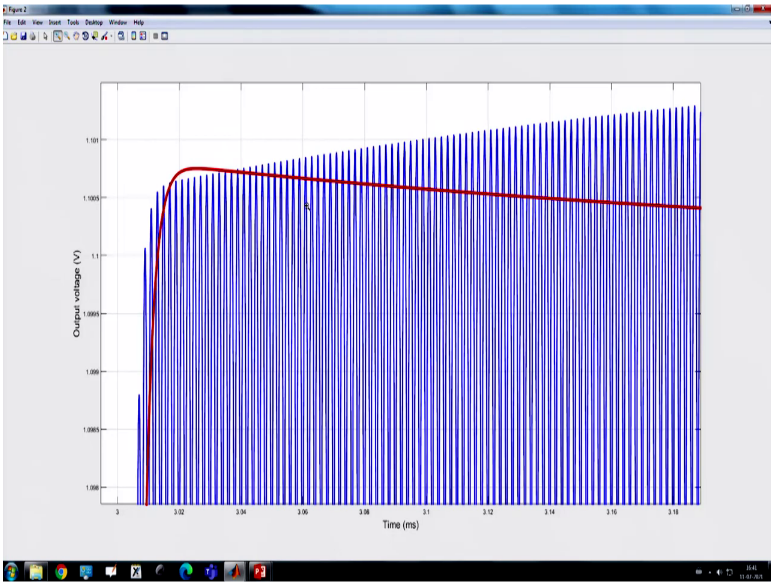

Now, we want to see match this response and see what happens ok. So, we want to compare you see the red one is the response obtained from the first-order model and the green one a blue one is the actual switch simulation actual switch simulation ok. So, this is like a first-order system and since we are using a PI controller.

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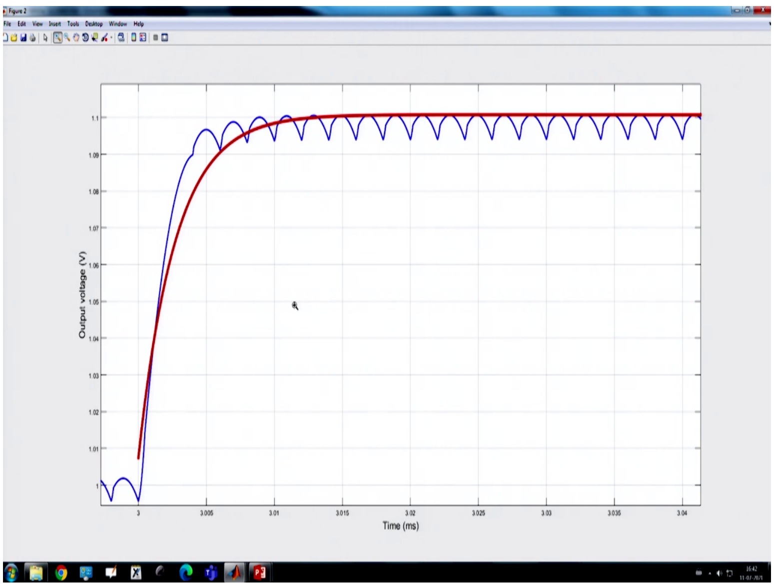

So, this is coming from though they are not matching exactly, but they are reasonably matching right, at least if you see the initial phase here; that means there is a model matching problem. So, here we should reduce the controller gain in order to reduce you know the bandwidth because we are going for one eighth of the switching frequency where there could be a model matching problem. Another aspect we want to see the model matching problem can be due to the first-order model. So, we do not know ok. But, let us do one thing if we reduce the controller gain; that means, you know, instead of using very high controller gain.

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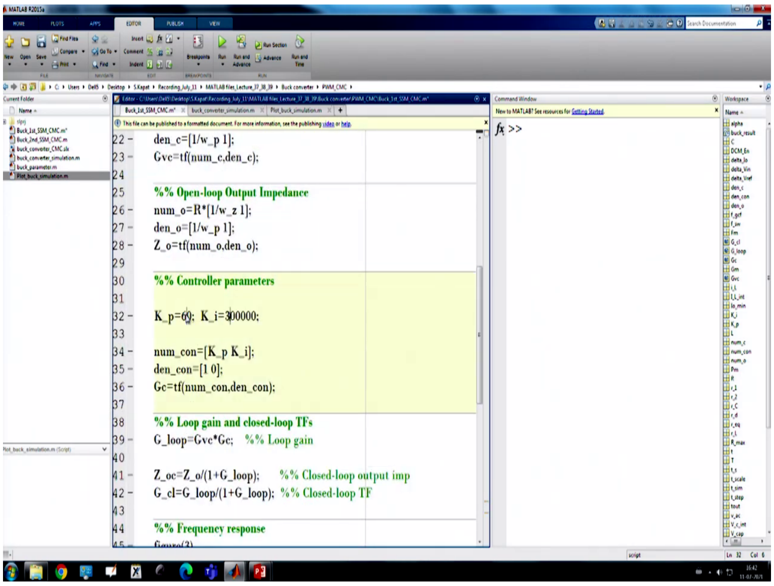

So, if we reduce to 60.

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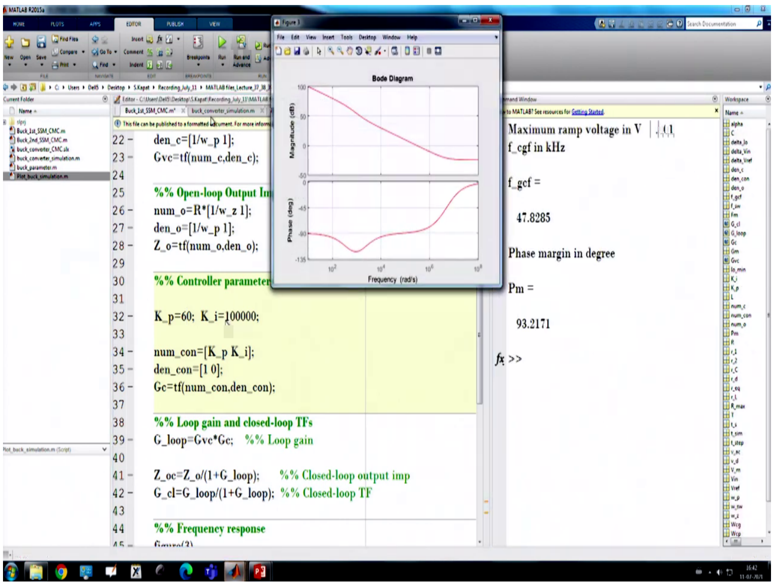

And if we reduce to this and let us again try.

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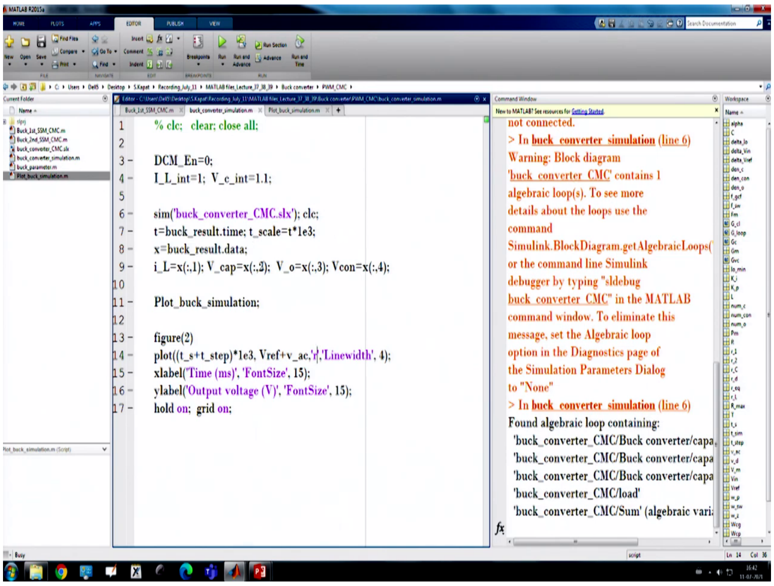

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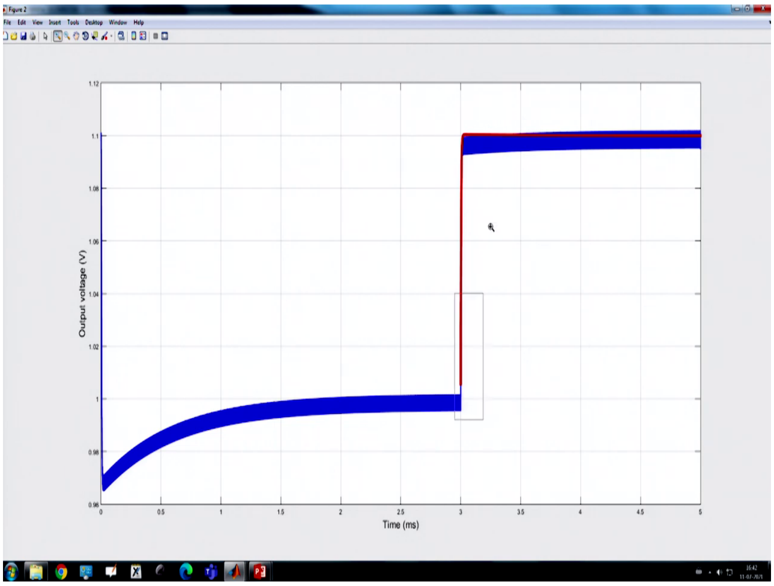

Now, it will show all the bandwidth ok.

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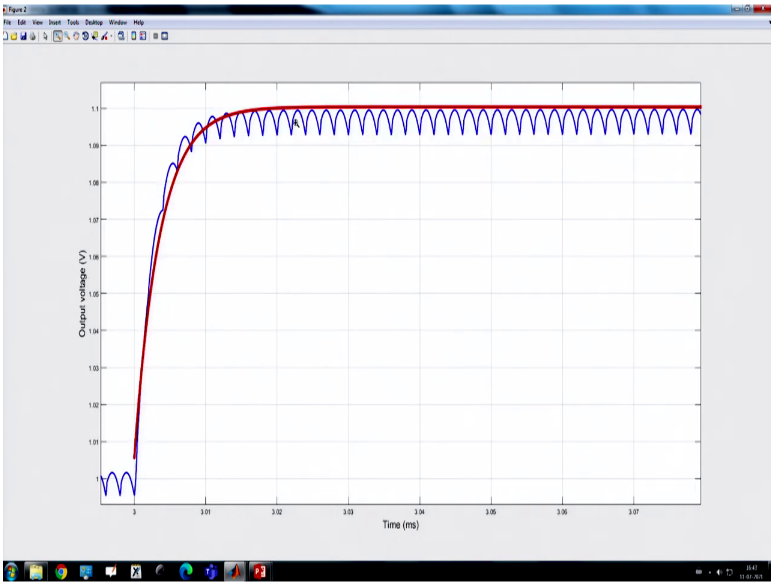

Now, this time, the model is matching to some extent except there is a shift in the DC value; that means, you see there is a DC shift. The red colour is shifted up slightly ok.

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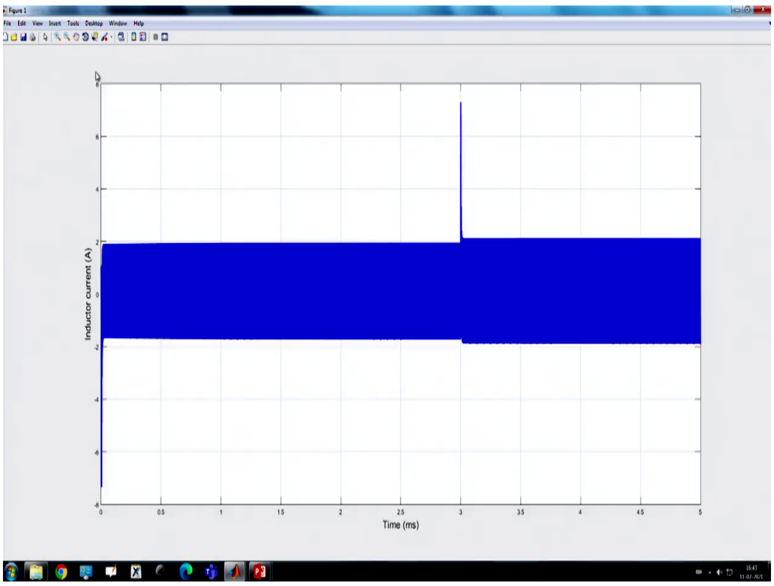

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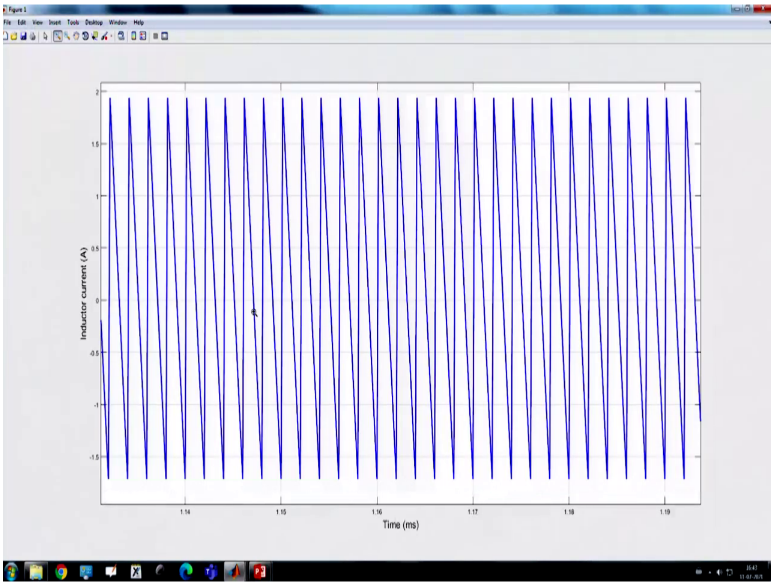

This DC shift is coming because of what? Because if you go to the current waveform you see we have taken that peak current we are controlling peak current, but we have assumed the control current is equal to peak current, right.

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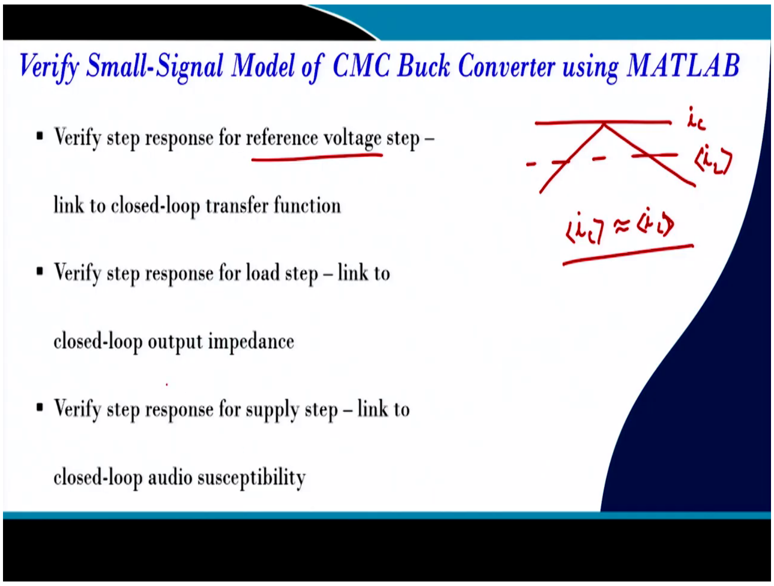

That means if you go back to our initial assumption, what was our assumption our actual control is like this; this is my control current and we are taking this is my average inductor current. So, we assume that this control current is approximately equal to i L.

But unfortunately at light load condition, particularly if you see the waveform here, your peak current is roughly around 2 ampere whereas, the average current is just above 0 very low. So, this can cause some DCC problem. So, weather can we solve this problem by increasing the load current or decreasing load resistance.

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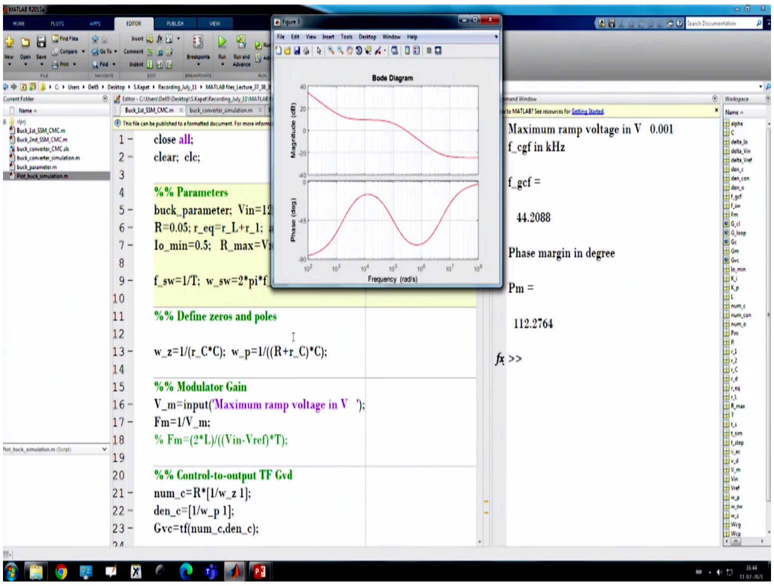

Suppose, if we use 0 0 5, 0 5 then we now we are operating at almost 20 ampere current ok. Now we want to see what happened. So, now gain crossover frequency is reduced. It is less than 1 10 because you are using a lower controller gains smaller controller gain.

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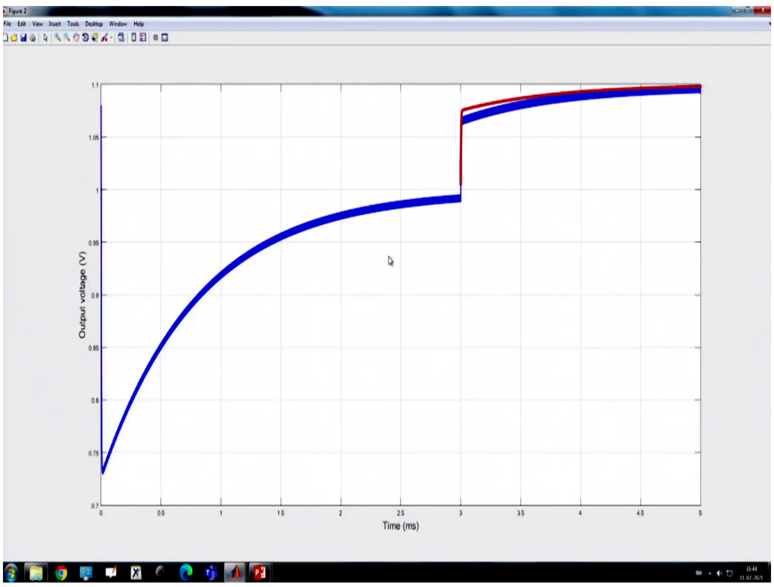

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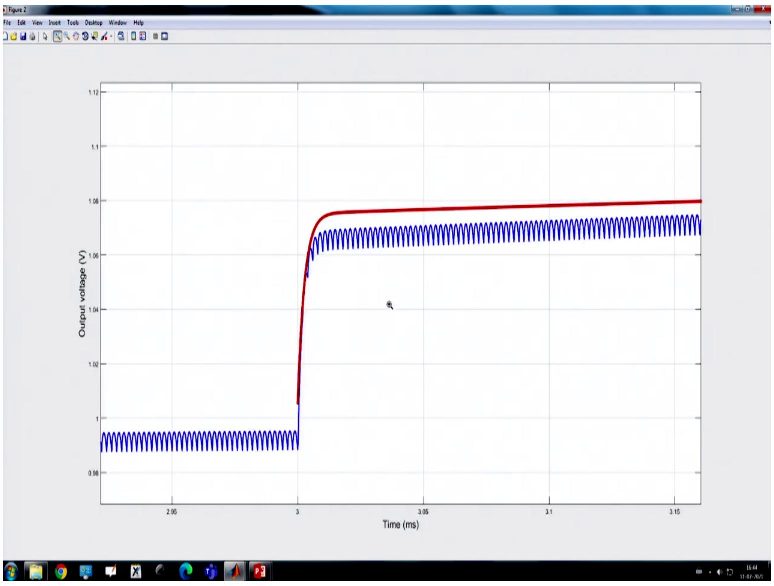

But we want to check whether the matching is still mismatch is still there or not ok. So, actually integral has you know we need to increase the integral gain because it has not reached steady state.

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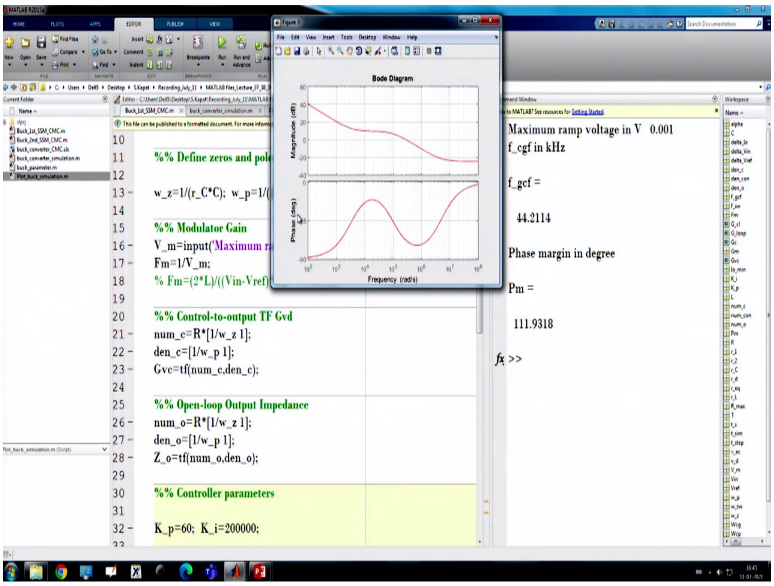

So, we need to increase the integral gain. I will tell you why? Because if you go back to our past. So, this omega P what is omega P? Omega P is our 1 by RC right. If you reduce, this pole becomes faster right, but at lower the DC gain is also falling right because at lower resistance value we are reducing the resistance value. The DC gain is drastically falling as a result it will take longer time; that means, the lower DC gain it will take longer time to reach to steady state.

So, in order to anticipate you have to increase the earlier we are using in one case in 10 ohm and the other case we are using 0.005 ohm. So, that means, we have reduced significantly this R value. As a result, your DC gain is also falling is also getting reduced and that is why it is it becomes sluggish. It takes a lot of time to reach to steady state ok.

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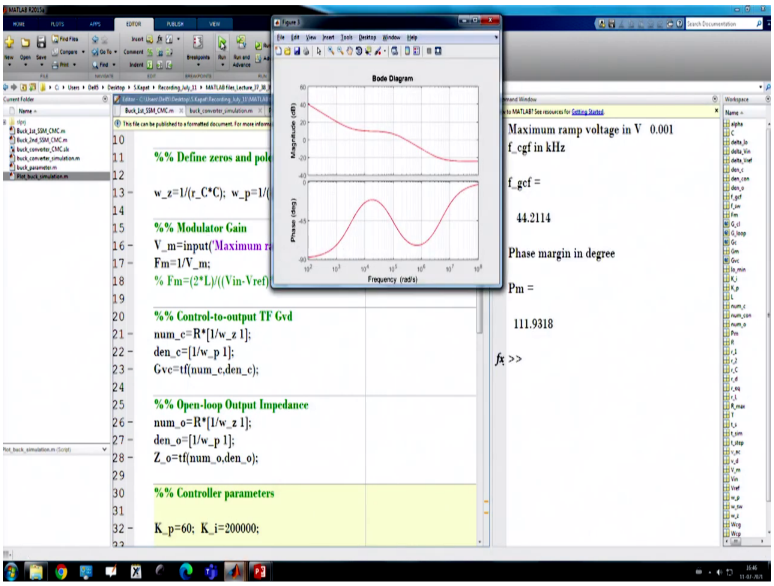

So, then how to solve this problem? We can simply increase the we have increased the integral gain and let us see in order to you know now it is slightly faster.

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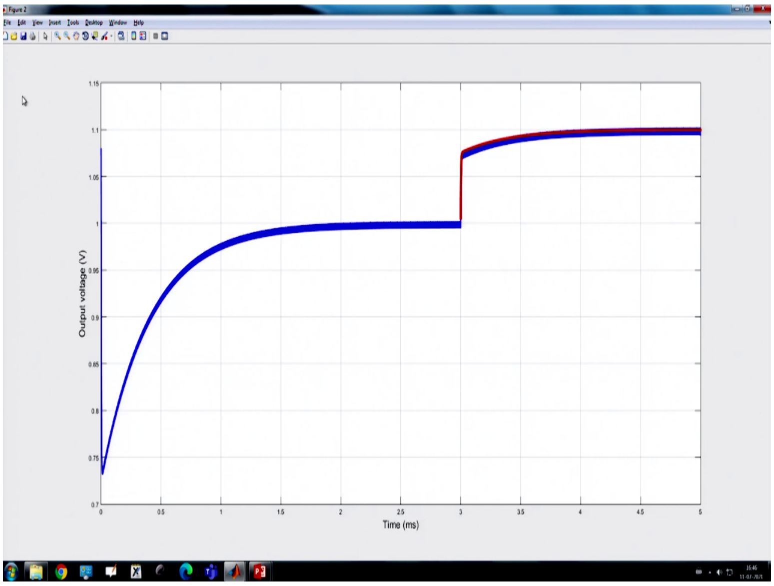

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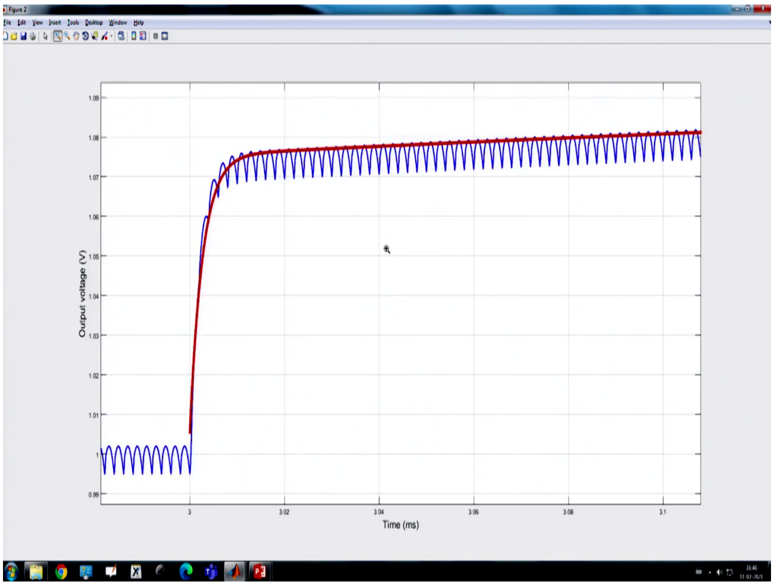

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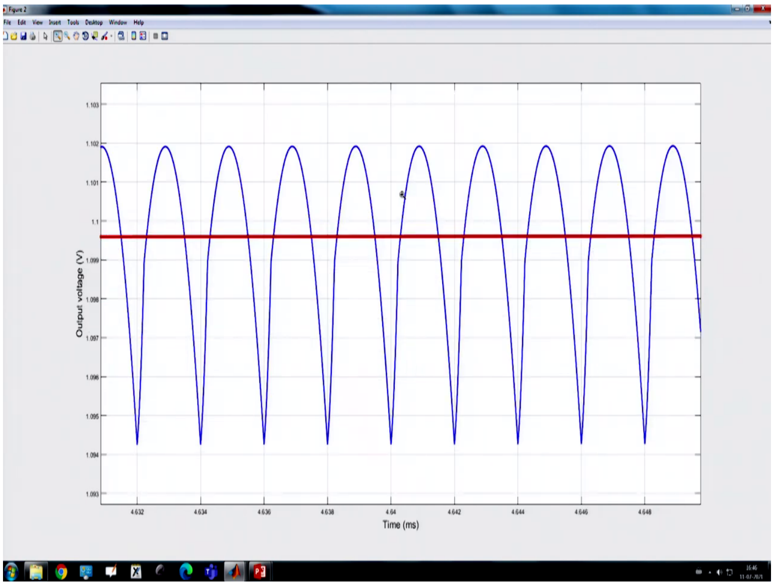

So, it looks like now they are matching closely. Now you can see the DC matching problem they are closely matching because earlier the mismatch, one of the problem with the mismatch, was our initial assumption; that means, we have taken the control current is equal to the average current, which makes sense when the load current is high because.

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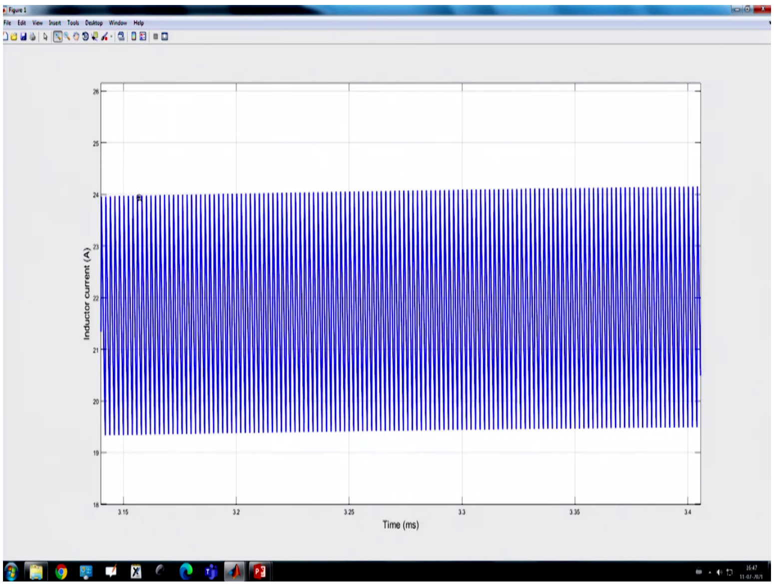

If you go back if you see here you know if you see here your peak current is 24 ampere and average current is 22. So, if you take the ratio that peak by average by peak that is almost close to 1 is not very low, but earlier we took you know the average was close to 0 and peak was 2. So, there is a significant deviation and that was causing the problem in this case ok.

So, that means, this actually tells us that this model limitation. This assumption itself makes this works fine when you are talking about high load condition ok. Next, we want to verify the step response for the load step transient ok go back to our simulation result and we want to verify for the load step transient.

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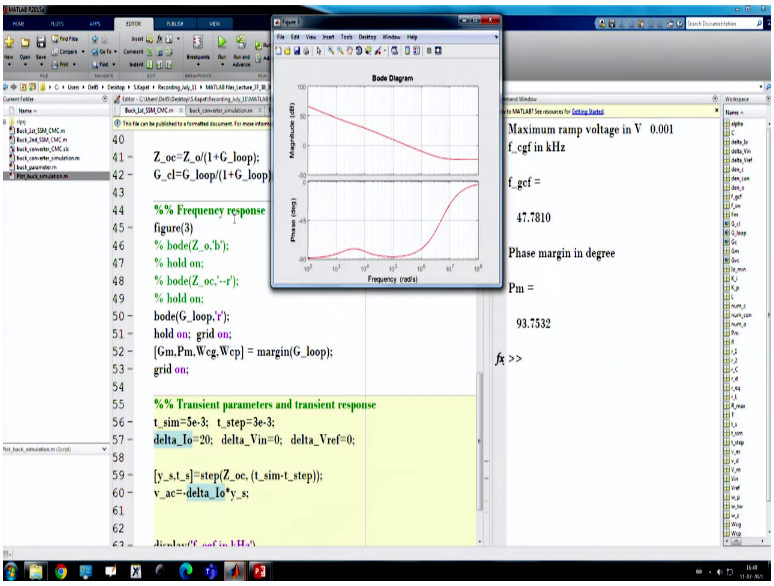

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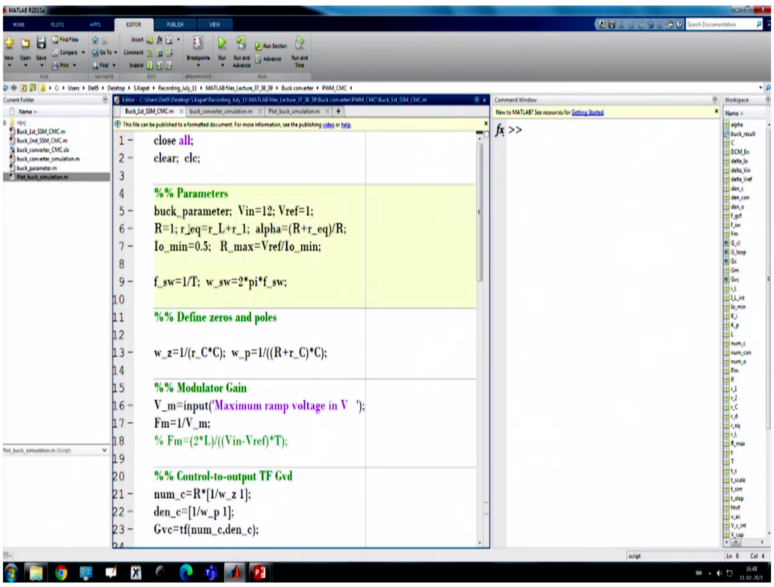

So, if you go to low step transient now what we have to do we need to set let us say we are making 20 amperes and we are may putting the resistance initially 1 ohm we want to change from 1 to 20 ampere 1 ampere to 20 ampere ok. So, here this part I have discussed earlier I have to set closed loop output impedance and I have to multiply with now we are applying load step transient ok again 0.01 and we want to check what happened with our simulation.

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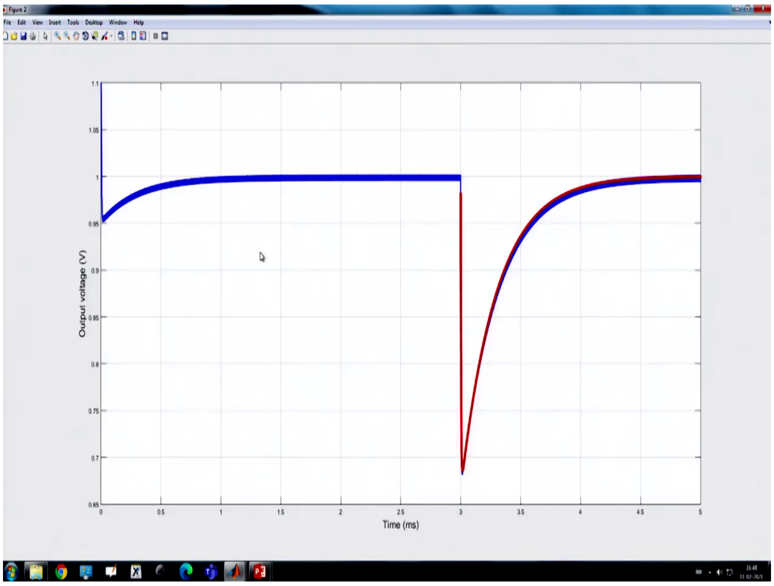

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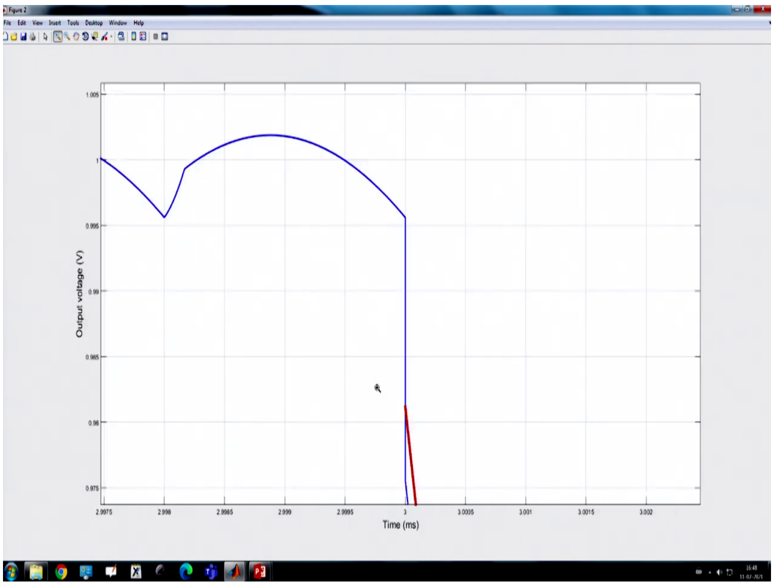

So, it is showing load step transient and you can see this initial jump is closely due to the ESR jump because you see there is a ESR jump.

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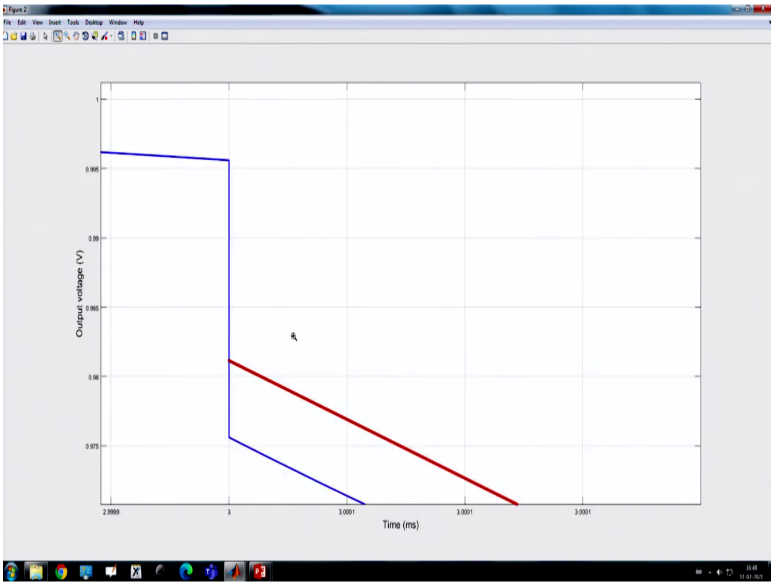

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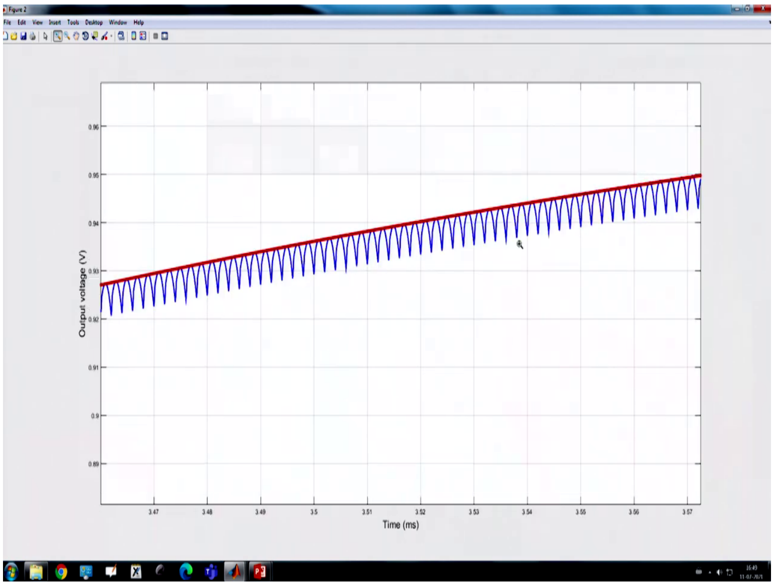

So, they are it is closely capturing the ESR jump ok, and that we saw in our earlier small-signal model and you can see the response is matching reasonably accurately. I mean quite nice.

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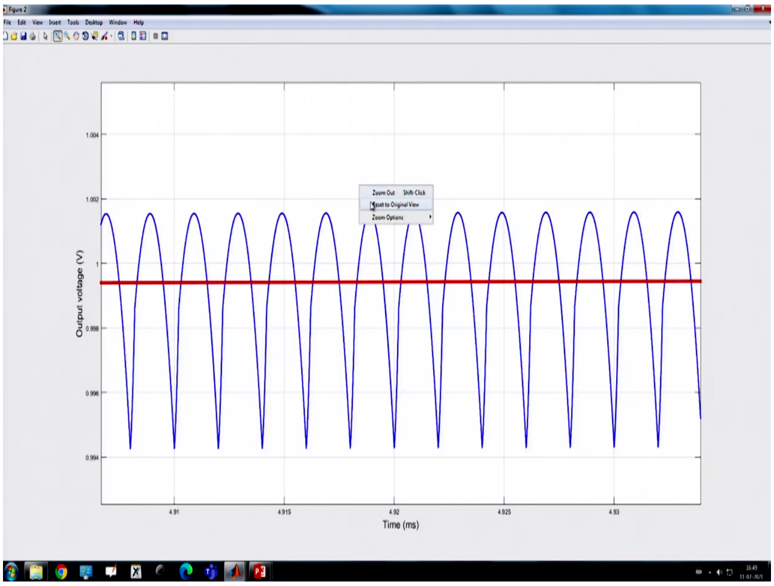

You can see they are coming close. So, that means, this first-order model works fine as long as and here the load current is undergoing transient from this to this ok.

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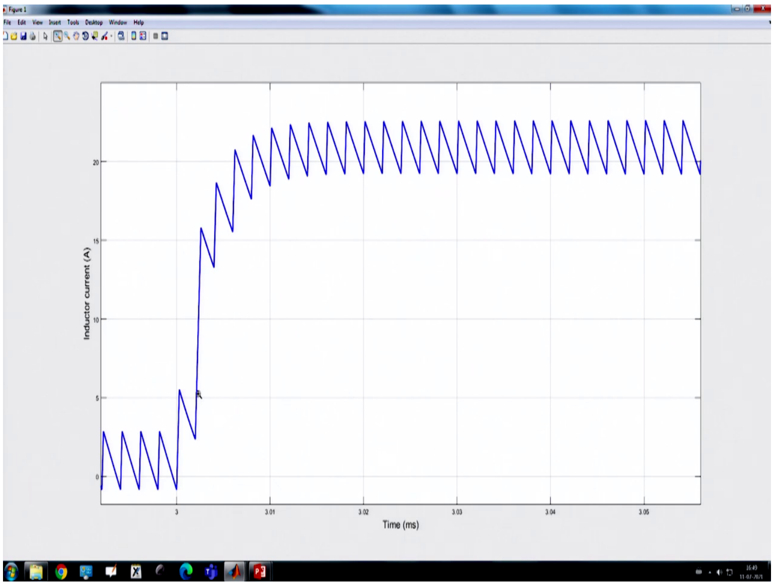

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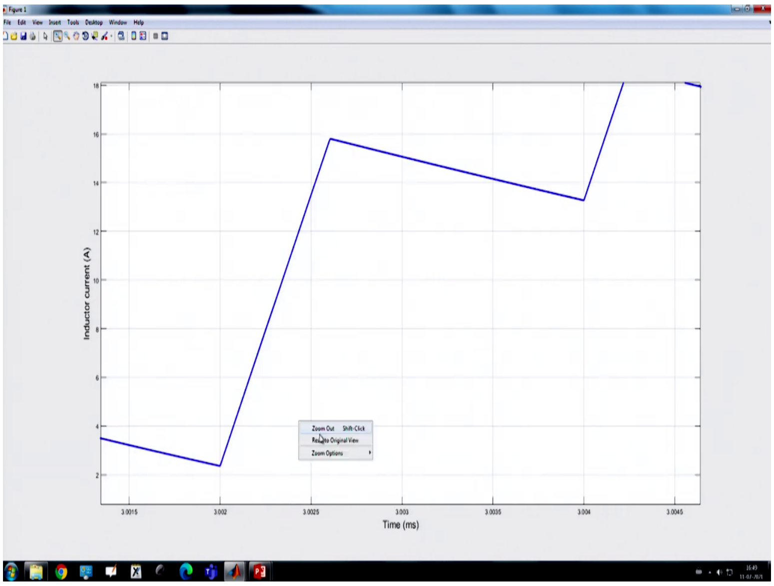

Even with huge duty ratio variation, because there is a large variation, particularly this particular cycle, but still our model is working reasonably well. So, it is well, we can design. The next part you know supply transient. So, since audio susceptibility is 0 so, there is no question, but this can cause some problem. So, now, even with our you know for our case if we do supply transient. So, we want to see we are assuming these models tells that there will be no change in the output voltage if you make a change in the supply volt.

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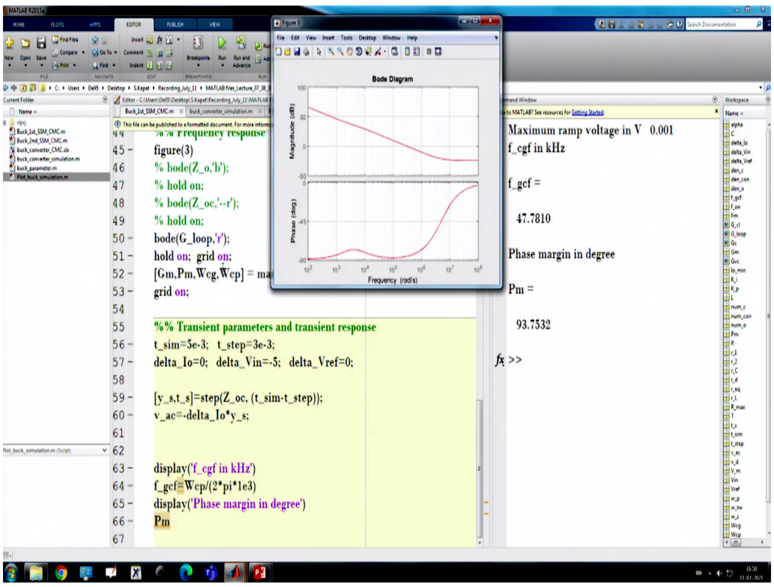

So, we want to make now supply transient. So, load transient we have removed let us say we are making minus 5 volt supply transient so, ok. So, we do not want to plot because you know supply chain is 0. So, this plot we want to avoid ok.

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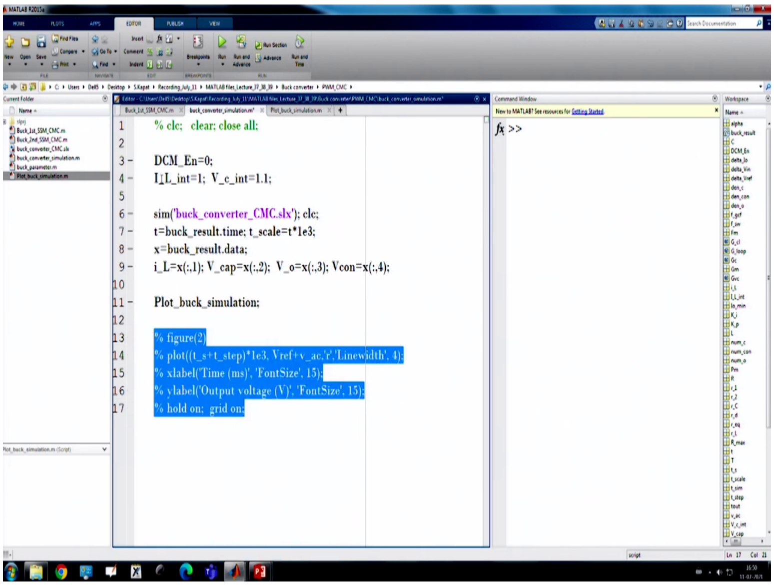

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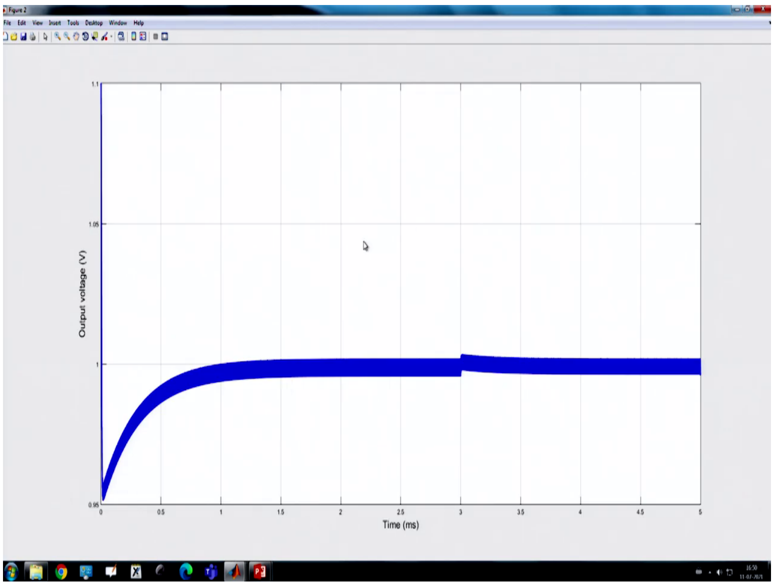

So, 0.001 and the next is that we want to show. So, we made a supply transient. So, our model says there is no effect, but actually there is a slight effect, although it is negligible.

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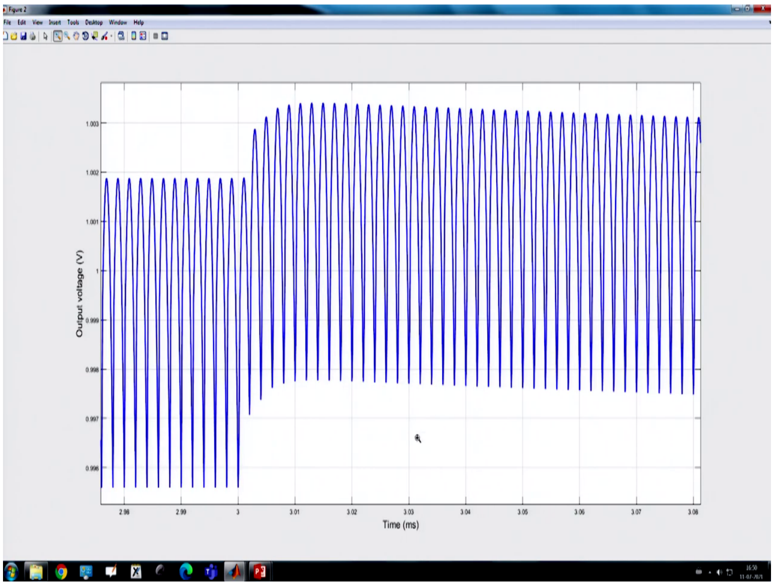

So, that means, it is reasonable you know the current mode control has a very like excellent you know audio susceptibility or you can say the line regulation. So, there is no problem.

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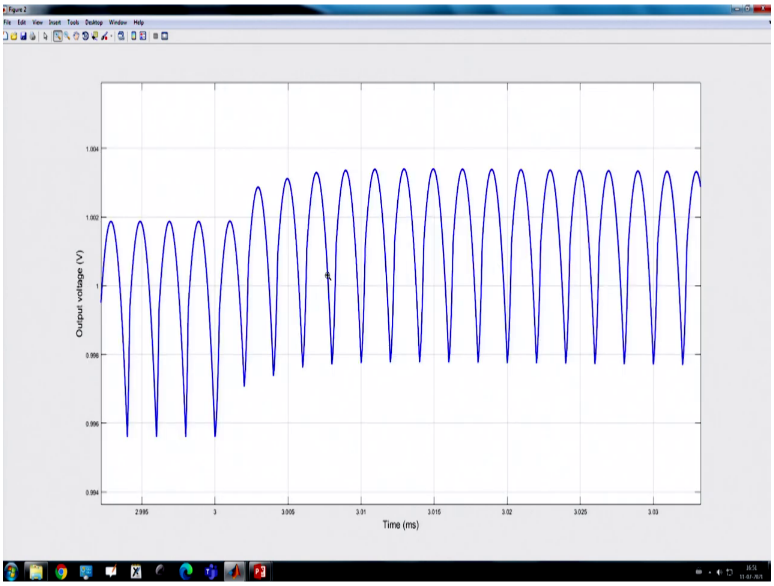

So, it immediately responds there is almost no change because it happens in the order of you know even less than 1 millivolt I mean few millivolt in less than like 1 or 2 millivolt ok.

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So, that means, we have checked, but limitation of the first-order model we have identified. So, there can be inaccuracy due to that whenever the load current is light, then the mismatch will come because the average is not the same. Second thing here, we have not considered the modulator gain. Because even though if you use ramp very low value, the model will significantly deviate if the ramp slope increase if you increase the ramp slow.

Because there is no provision in our model to accumulate ramp, that is one of the problem. Because a ramp is needed when the duty ratio is higher than or even it may be lower than 50 percent also like around 0.4 0.45 if you increase if you use a high gain you may get first like a sub harmony instability ok. So, that will be a problem when you use. So, ramp compensation that can cause some mismatch in this error.

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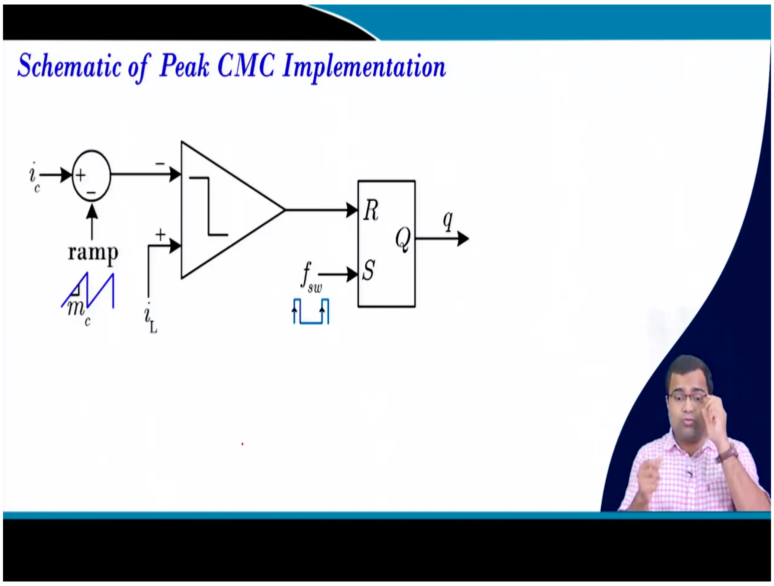

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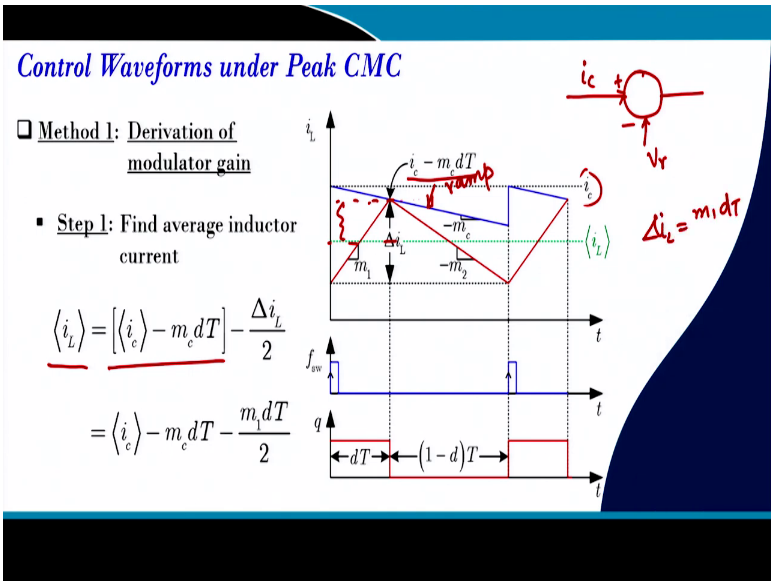

So, now we want to go for a better model. So, first we want to understand peak current mode control, then what we are going to do we want to improve the model accuracy. Now, we want to that actually lies with the derivation of the modulator gain, ok. So, if you the first approach if you take the first approach, it is I know derived by the middle brook approach where we are taking a ramp compensation here.

So, this is our ramp this is our due to ramp because we are what we are doing here we have a reference current this is our i c here and we are subtracting ramp because we can add ramp with the current or we can subtract the ramp from the control voltage control current.

So, that is exactly what we are doing, and this is my ramp basically minus of the ramp and then we want to derive the average current expression in terms of this current that we earlier we took i L average equal to i c average, but now we want to introduce the duty ratio information.

So, find the average current. Average current here in this case is nothing, but this point minus half of the ripple right. So, this is minus half of the ripple, half of the ripple. So, it is what is this value this value is given here. So, average of this minus delta i L by 2 and what is delta L by 2? It is you know what is delta i L delta i L we have learned earlier it is m 1 d T right. So, delta i L by 2 is this.

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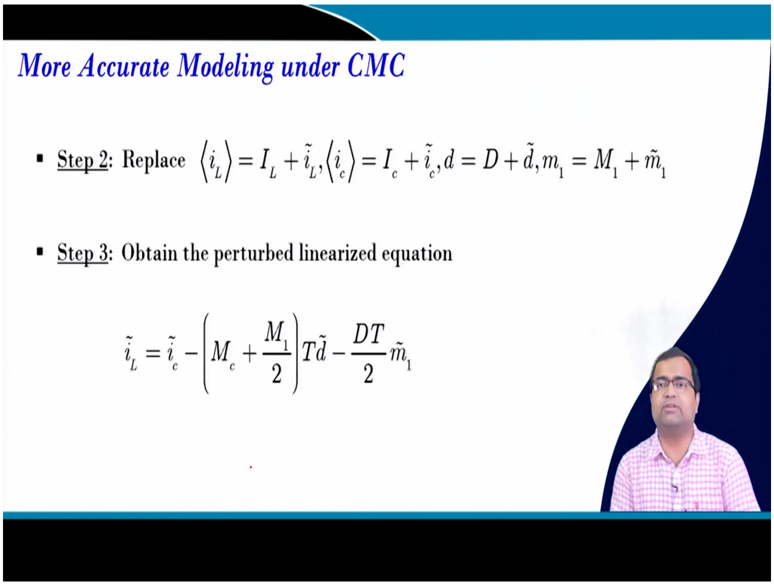

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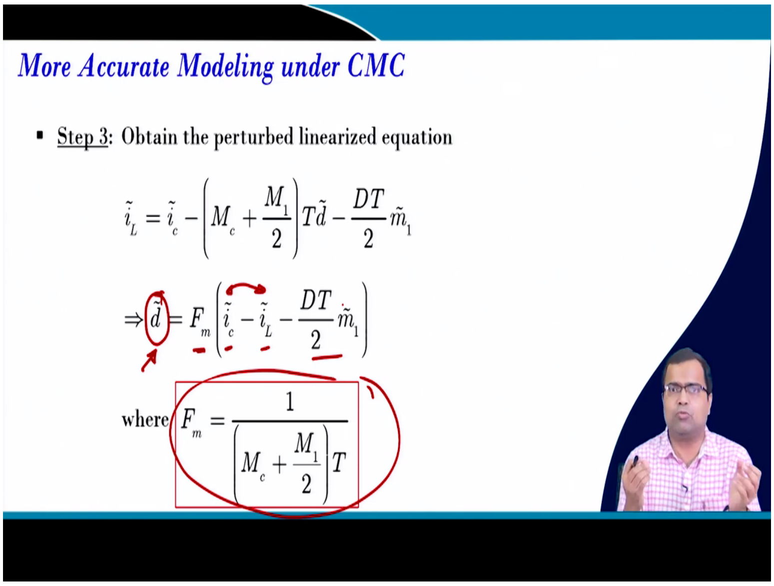

Then step 2 you can now consider the steady state quantity and perturb quantity and then obtain the perturb equation. So, from there if you obtain the perturb equation you will find out that the perturb equation the duty ratio perturbation can be written in terms of modulator gain, control current, inductor current and this.

So, earlier these two were taken equal. So, that is why that there is no duty ratio expression, but now we have not taken equal and this is a modulator gain right. So, this is something similar to what we did earlier that we are trying to find out the duty ratio expression here in terms of control current and also inductor current and M 1 will also carry voltage input output voltage information.

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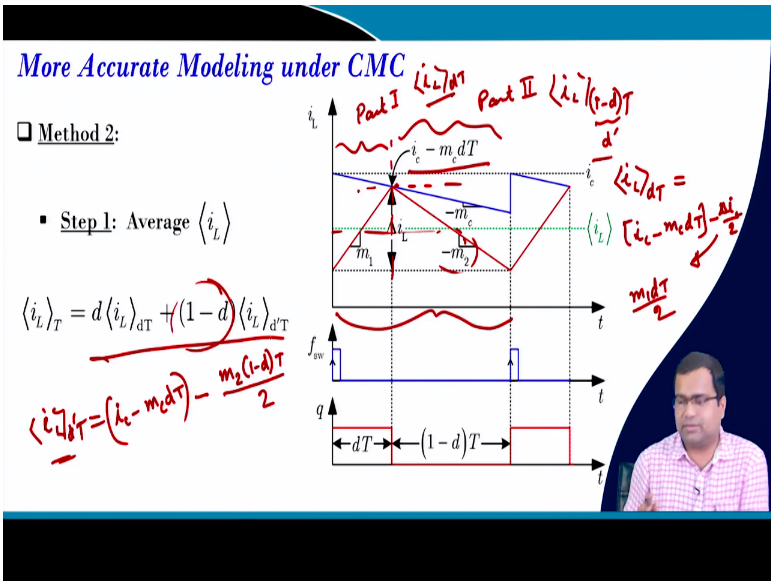

Method 2 another way now average inductor current earlier, we took that only for this cycle; that means we have only considered this cycle. The average inductor current was equal to this value minus half of the ripple, but this may not capture the full picture. So, we want to take the average inductor current over the entire cycle; that means, here the average inductor current is nothing, but if I take the average inductor current in part 1 this is my part 1 and this is my part 2.

So, here the average inductor current is averaging over dT time and here I am averaging over 1 minus d T times or d dash time. Here I am taking 1 minus equal to d dash. So, then if we average the overall average d into this 1 minus d into this is exactly is done here.

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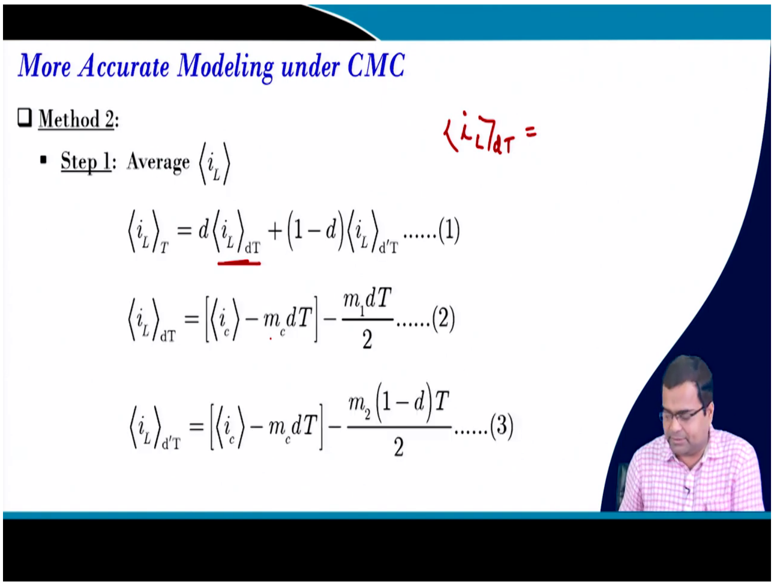

Then if you apply, you know substitute that equation what is i L average during dT time. So, i L average during dT time is nothing, but that you know if you go back from the waveform in this interval, it is nothing. But i L average dT time is nothing but this value; that means, i c minus m c d T minus your delta i l by 2 which is nothing, but m 1 dT by 2.

Next, what is i L d dash T? So, this point is common for this right. So, it will be i c minus m c d Tit is there, but now minus half of the ripple will take in terms of this slope because we are talking about this particular sector, right? So, ripple can be expressed in terms of falling slope. Also it is m 2 1 minus d by 2 divided by 2 and if you multiply 1 minus d this will be square ok. So, this is exactly what we are doing here i L dT.

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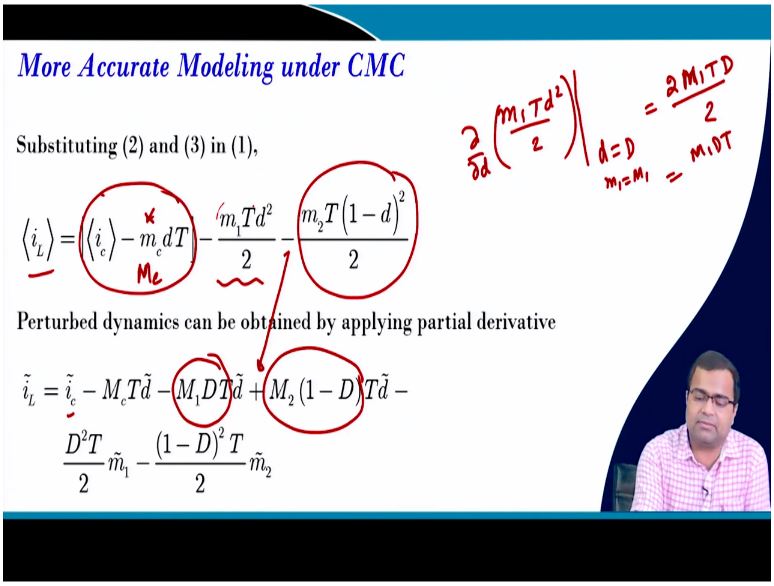

And then you substitute you will get this term now you perturb. If you perturb, then you can i L perturbation and since d 1 minus d both are this term is common. So, they will add up and become 1. So, i c perturbation and since this is constant, so, in fact, we should write m c directly here we are not perturbing the slope.

Then, for this term once we will consider perturbation, the duty ratio and the other time we will consider perturbation, the slope ok. So, if you part consider perturbation, the duty ratio. So, m 1 T d square by 2 then we simply partially differentiate with respect to this and that is computed as d equal to capital D. Then what we will get? We will get 2 times m 1 T and this is computed at m 1 equal to capital M 1.

So, this will be capital M 1 and this into D divided by 2. So, it is simply M 1 DT. So, this is exactly here. Similarly, you can take the partial derivative of this with respect to DT ratio then we will get this term ok and there will be negative sign and negative. Negative becomes positive this term will become positive and similarly you can take perturbation the time I here. So, then this term will be fixed. So, this is simple.

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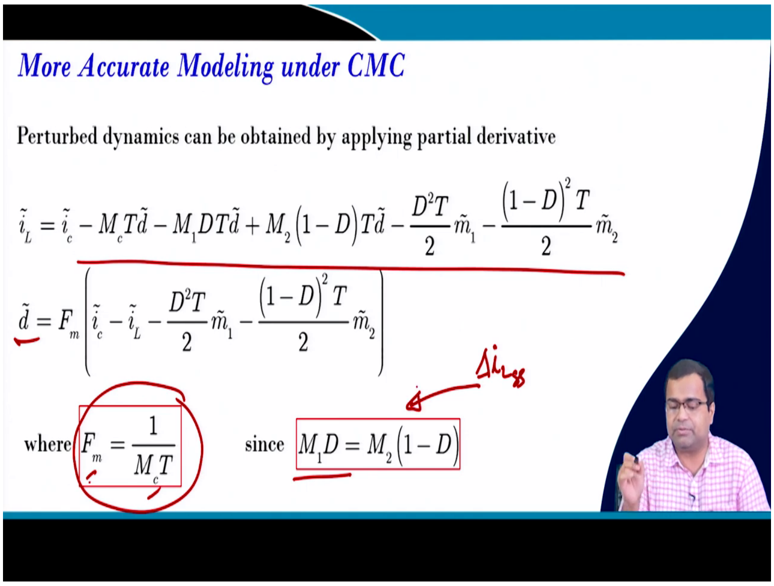

By that we can obtain the duty ratio perturbation, you know, because we have already obtained this. Now, we have to take due to issue perturbation the left side and all other terms to the right side. Then whatever will be divided F m that modulator will be M c T; that means, in this case, the modulator gain is purely M c dependent compensating ramp and that is why in the earlier simulation we took a very small M c.

If you do not take M c M c equal to 0, then this F m becomes infinite right; that means, without ramp compensation this will become infinity, but if you take a very slope in F m. Then I will show you for a higher F m or smaller M c this model. What we are going to derive will almost resemble the model of the first-order model ok since you know at steady state M 1 D that the coming from the; that means, steady state ripple. This is coming from the steady state ripple criteria.

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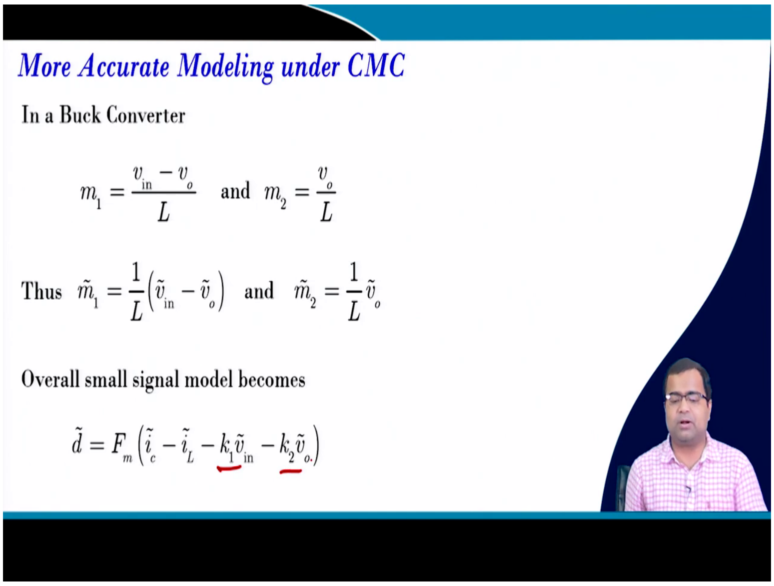

So, in a buck converter you can write m 1 m 2 perturbation. So, it will be so that means you can find out the term associated with v in perturb v 0 perturb.

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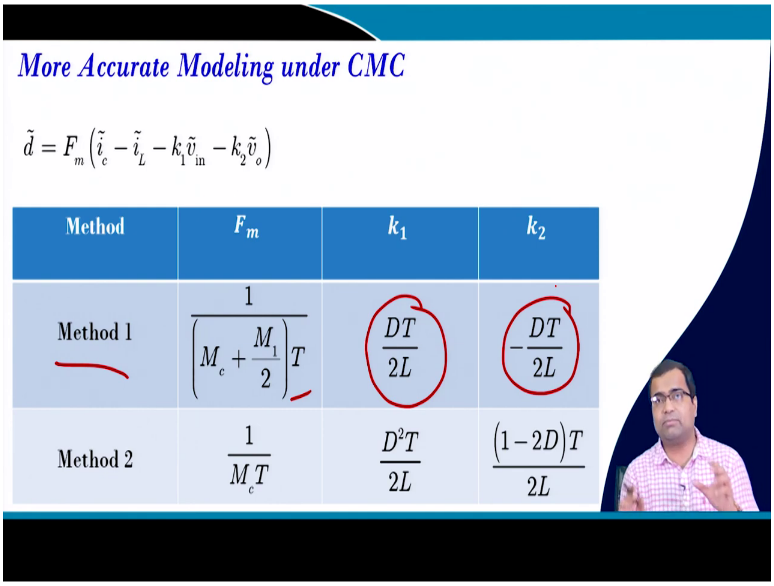

Then you can tabulate the modulator gain in method 1. The middle book method is this then DT by 2L 2 L minus DT by 2L then you can write 1 by M c D square t by 2 L. So, all this thing we can write.

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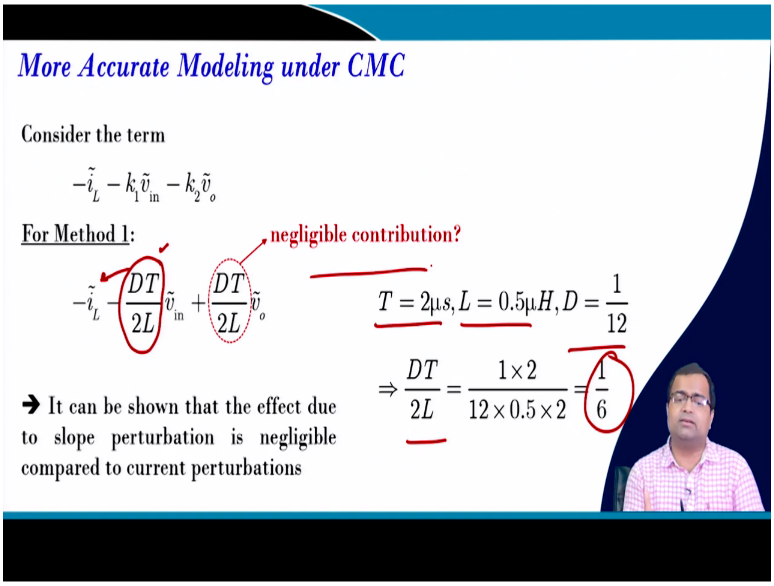

But interestingly, if you take in method 1 for example, if you take 2 micro second is our time period 0.5 micro henry is our inductor D equal to 1 by 12. So, DT by 12 only one sixth; that means, if you take compared to the actual inductor and scaling DT by 2 so, this has negligible effect. So, it has a negligible contribution ok.

So, we may drop this negative conclusion for sake of simplicity, but if you want, you can include it ignore. So, this term is ignored. It has a very negligible contribution, but we can you know include it if you want, then there will be an additional loop of the voltage.

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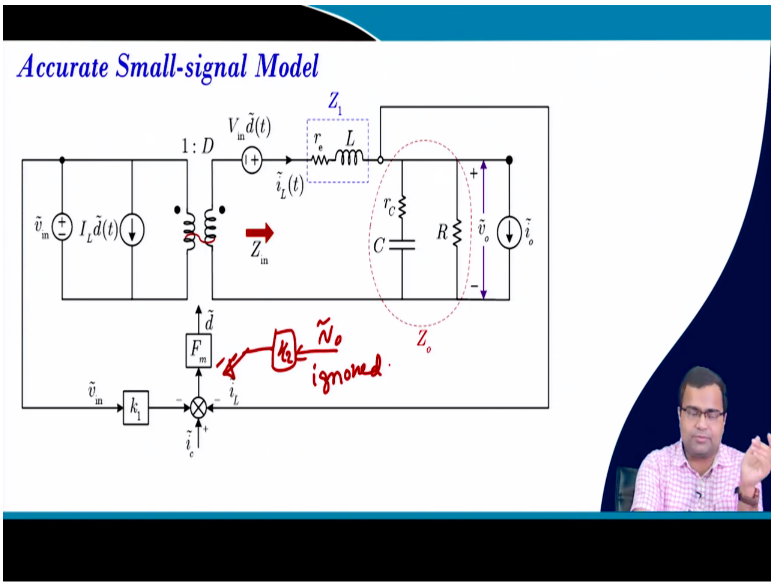

So, now this is our circuit that we have discussed; that means, since we have ignored the perturbation due to the output voltage, otherwise there would have been another loop which should come k 2 and there will be v 0 and this will be minus. So, this term we have ignored this term we have ignored because we have initially assumed that dt by 12 that term is very small ok.

So, now this is the loop structure. This is our original small-signal AC equivalent circuit of the buck converter which we have derived for voltage mode as well as open loop. Now we are putting this current mode control loop; that means, there is a current loop. You see the feedback current loop.

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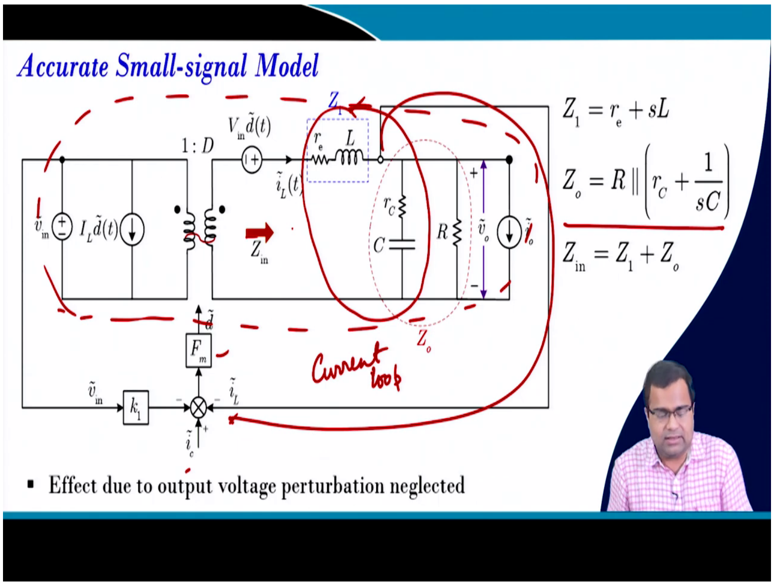

And this control current is generally generated from the outer loop. It is a 2 loop control. This is the inner loop. This is a current loop, ok which is the inner loop. There is an outer loop will be there if you close the outer loop ok. Now, this F m we have derived.

So, this can be obtained what is Z 1. We have taken this to be Z 1 and Z 0 is the output impedance of the buck converter, which was when we close the loop close the current loop for the approximate model. This was our output impedance. But if you sum these two; that means, if you take the entire branch in this circuit, it is nothing but the input impedance ok. So, z in so, the effect due to output voltage perturbation is neglected.

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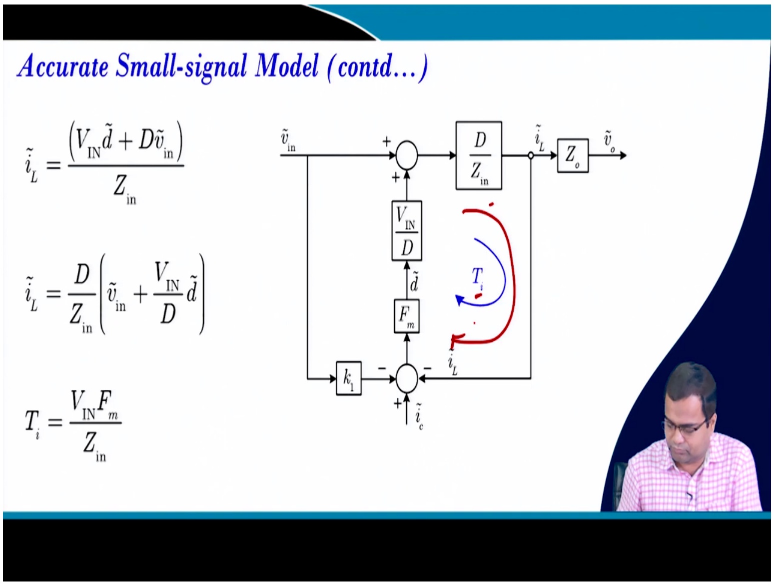

Now, this is the overall small-signal block diagram and you know you can simplify this i L from this block diagram. So, I am not going to talk about this. I want to find out what is my current loop transfer function. So, that can be if you take the whole product then it will be V IN F m by Z in ok. So, this is my loop transfer function.

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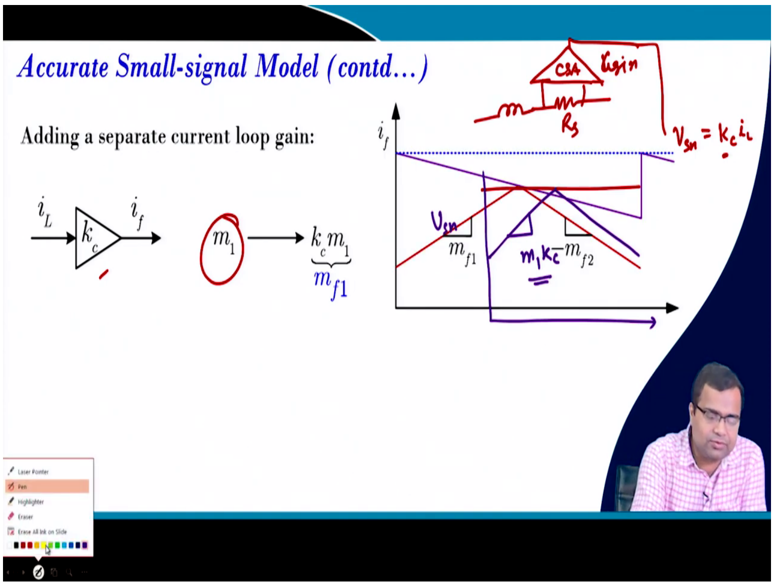

Now, adding a separate current loop gain. Suppose you put a current sense amplifier which has a gain which may not be unity because you want to scale it. This can also include suppose you have the sense resistance suppose you have used a sense resistance, sense resistance R s in with actual inductor current, but this sense resistance will also have current sense amplifier right. So, there is a current sense amplifier which will also have some gain the gain of the current sense amplifier right.

So, whatever we are getting the sense voltage we have discussed, it is nothing, but some current loop gain multiplied by your actual inductor current, ok. So, this sometime we want to reduce the gain because you know if you want to increase the gain that there is a gain-bandwidth product of the current sense amplifier because the high side current sense amplifier there are some dedicated commercial i c which has a limitation on the bandwidth.

And if you want and also a gain; that means, there is a gain bandwidth limit, but we can incorporate this k c as well. If we incorporate, then our m 1 slope because in actual I am talking about the actual current which is compared now. Now, this is our sense voltage which equivalent to current and this slope will be m 1 into k c because it includes the current sense amplifier and everything; that means, it is not exactly inductor current is a scaled version of the inductor and under this ok it is shown here.

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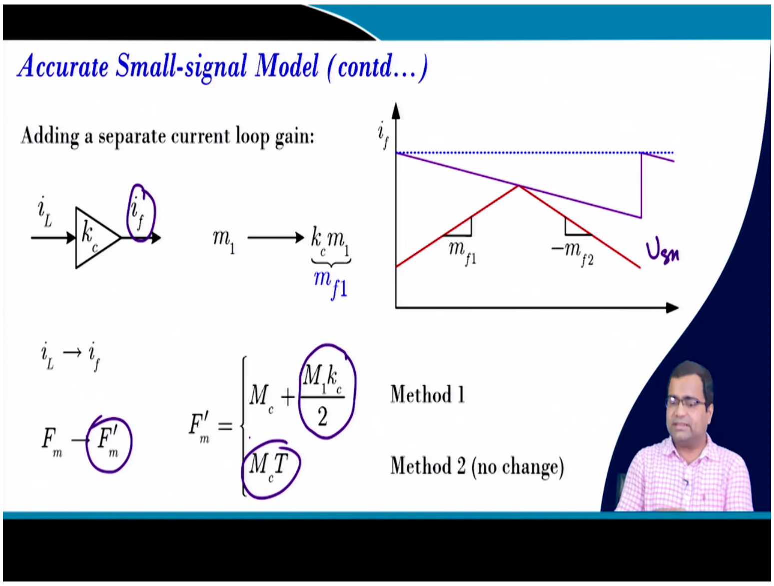

So, under this you can draw the waveform. This is my sensed voltage, as if it is like a filtered current or you can say sense voltage. Then modulator gain will also scaled up because if at all it has method 1 will always scale up wherever the actual current slope will be there, but for ramp it does not matter because ramp is independent of this.

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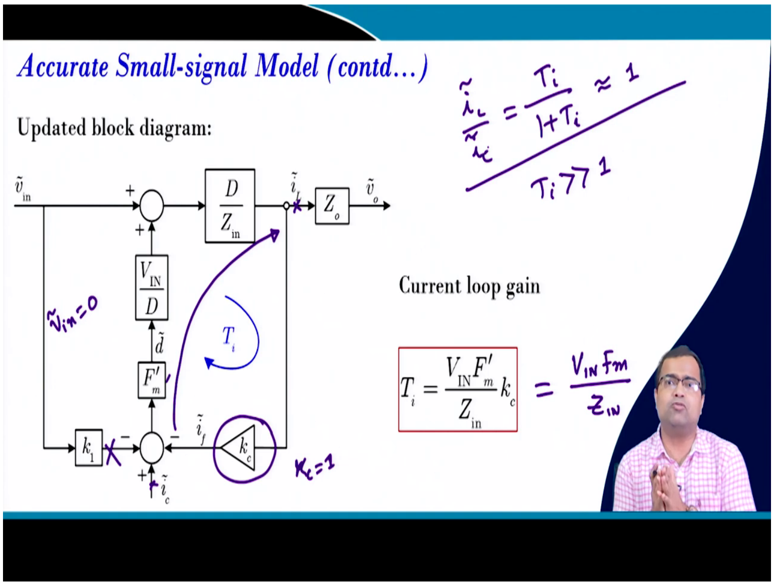

So, accurate small-signal block diagram can be updated with the current sense amplifier gain and we can modulate a gain. So, this is a current loop gain updated current loop gain.

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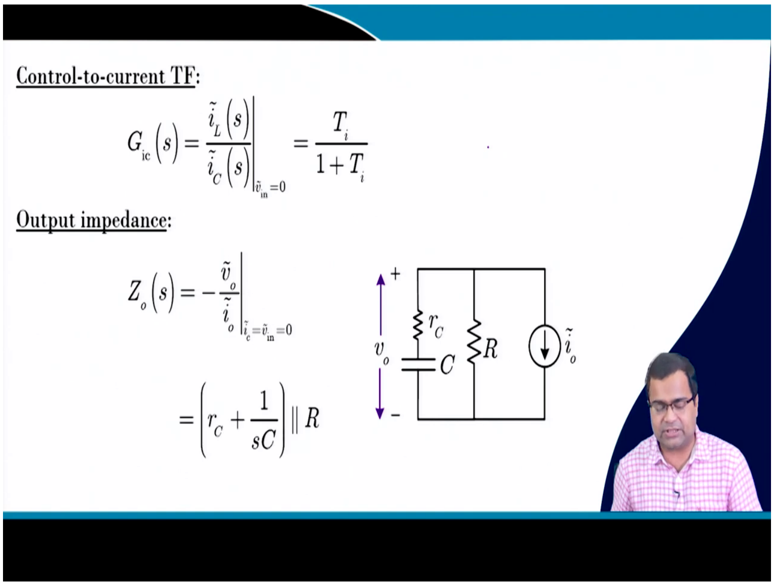

Now, control to output transfer function if we take this diagram ok. So, what is the transfer function between i L and i C? Suppose our v in perturb is equal to 0 so, I can discard this part then what will be my transfer function and suppose we take k c equal to 1 suppose we take k c equal to 1 then our t I will be V IN F m by Z IN ok. So, under this case, what is the transfer function between i L and i C ok. So, these 2 transfer functions. So, this will be simply this is in the forward path right. This is my forward path and since K c equal to 1.

So, forward path transfer function is same as the loop transfer function current loop transform. So, it is simply T i by 1 plus T i now if T i is very, very high if T i is very, very high. Then this will be approximately equal to 1 and we have started with the first-order model that i L perturbation is replaced by i c perturbation and those are correct as long as the current loop gain is very high ok. So, if the current this output impedance expression.

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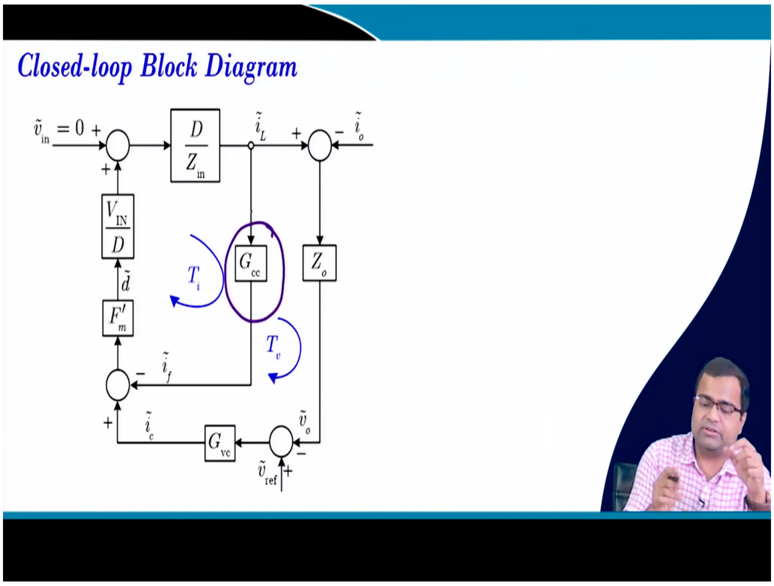

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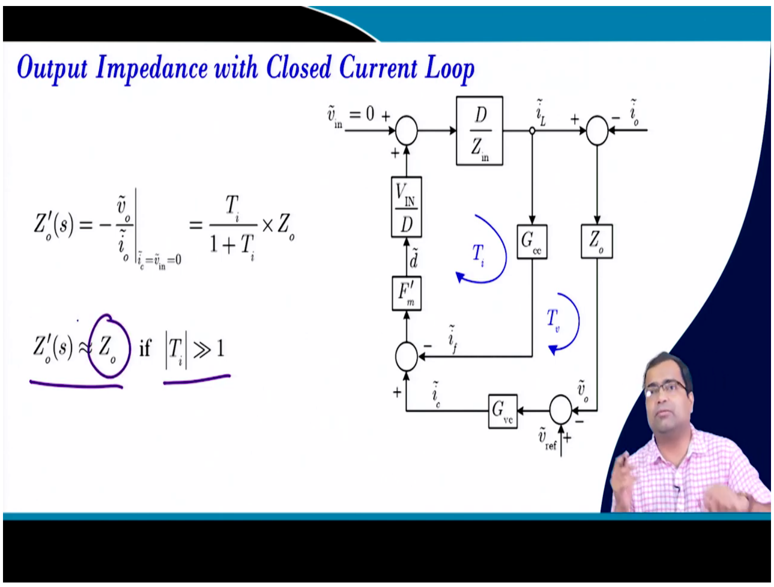

So, that means, closed loop block diagram if we consider you know current; that means, current sensor ok. So, closed current loop. Now if the current loop gain is very high, then the output impedance with this model will be same as you know the model of the earlier model.

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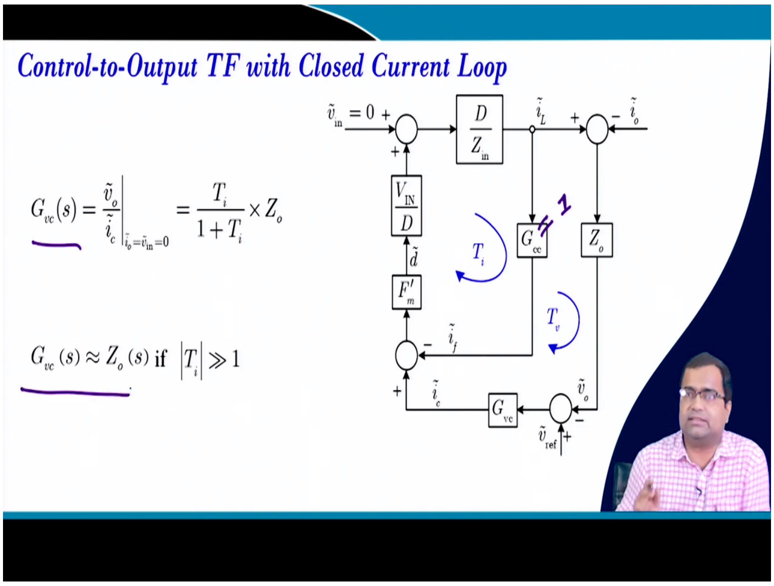

And here I am taking G cc equal to 1. Similarly, the G vc if the current loop gain is very high, it can be it is the same as these two right.

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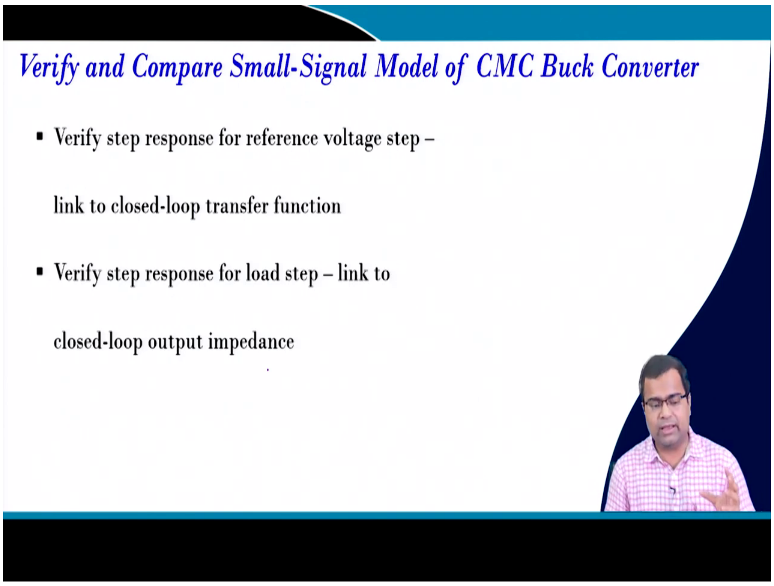

Now, we want to verify that means, you know let us go back to the MATLAB and we want to verify. So, now, we want to verify this 2 model ok.

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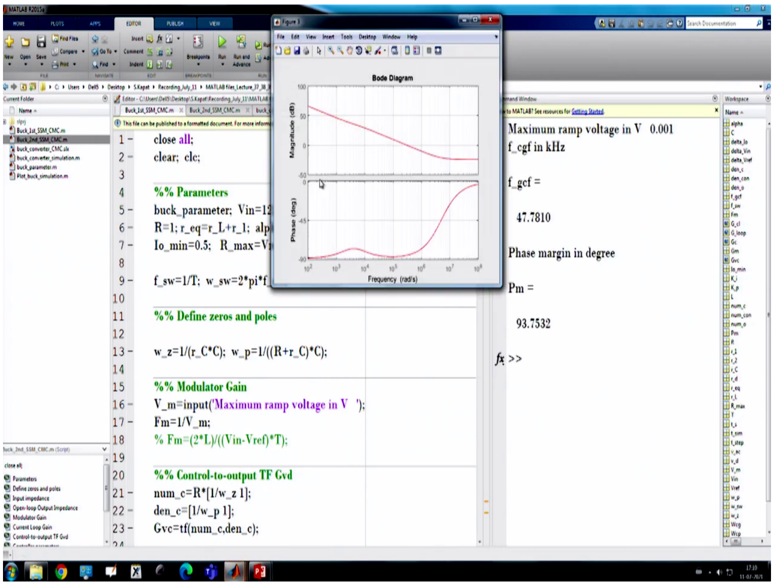

So, one case we are using 0 0 1 ok and this is a loop transfer function of using the first-order model.

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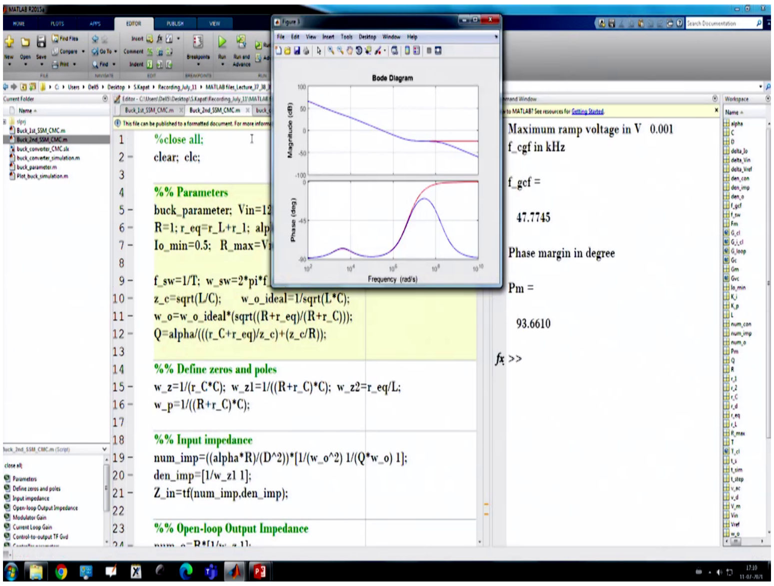

Now, same ramp, we are using 0.001 and this is a loop transfer function and we want to compare ok.

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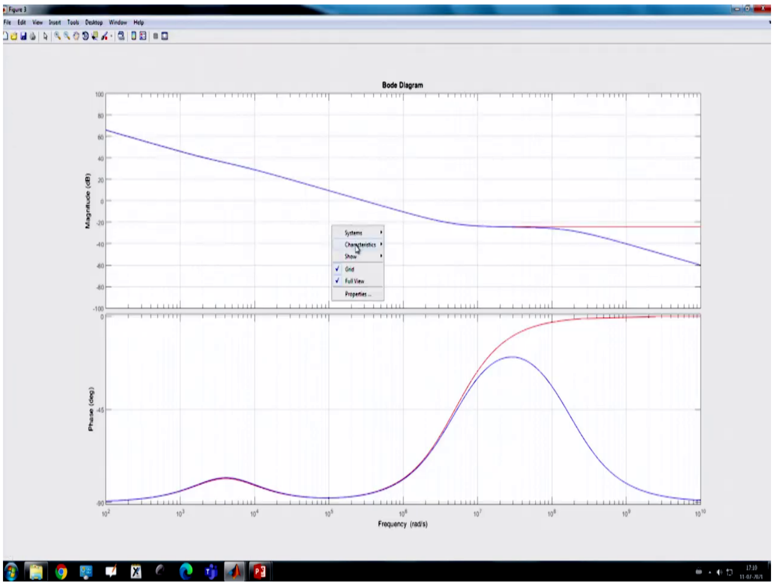

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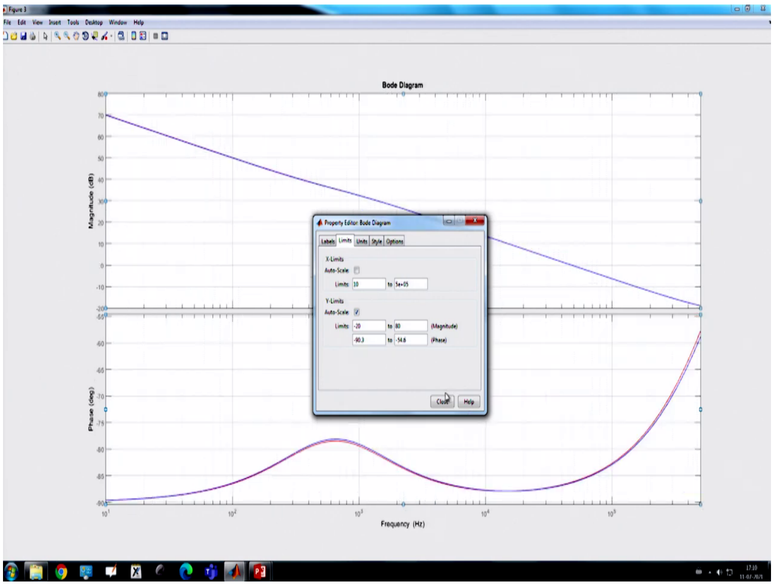

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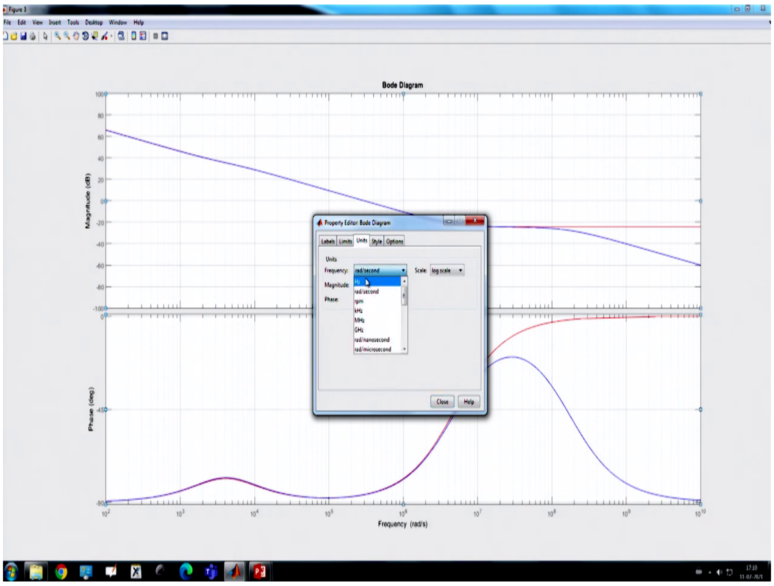

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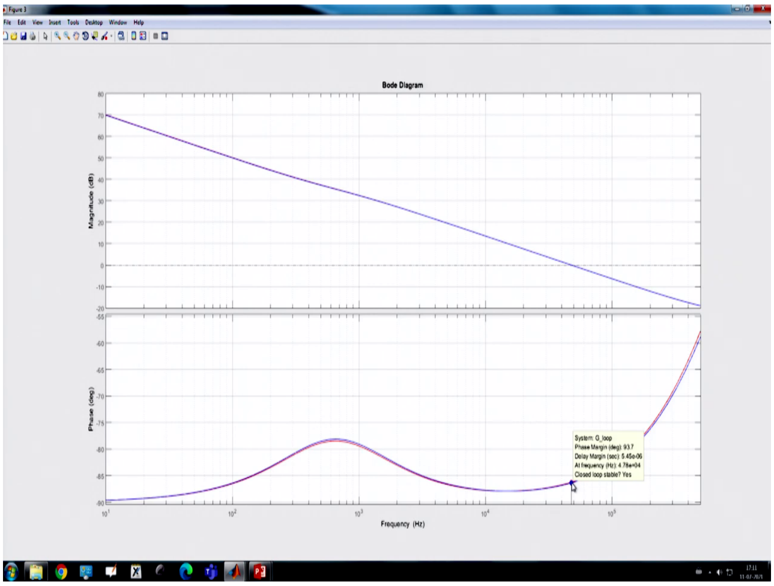

So, let us first set the heart in frequency and limit we set 0 5e minus is 5 ok; that means, this is our switching frequency and you see the loop transfer function, what are the stability margin. So, it is phase margin is 93.7 and frequency is 4 47.8. It is like almost one 10 switching frequency and they are matching quite nicely because both are almost overlapping.

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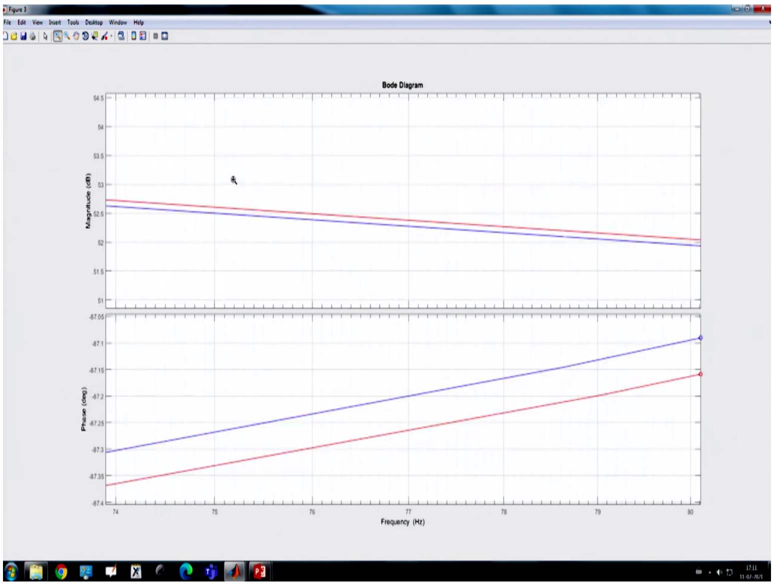

If you go further down, they are almost overlapping ok. So, they are overlapping and they are almost close. So, it is expected that their transient performance will be also it should match.

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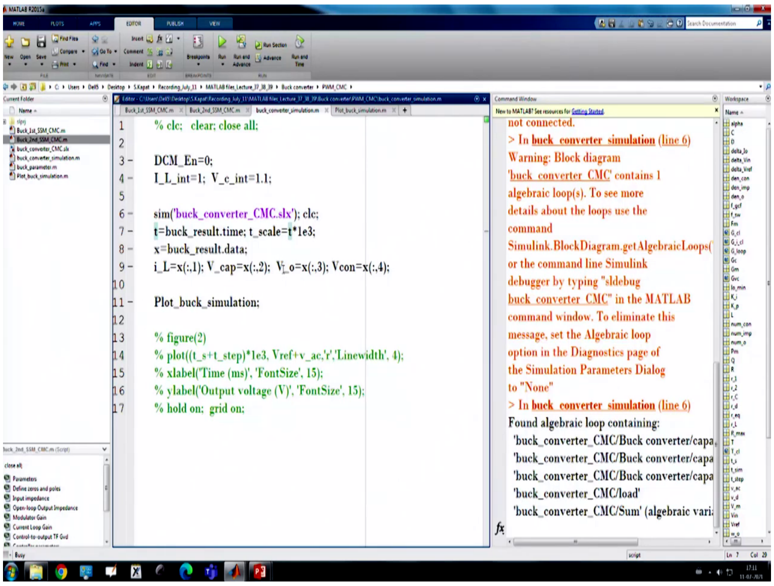

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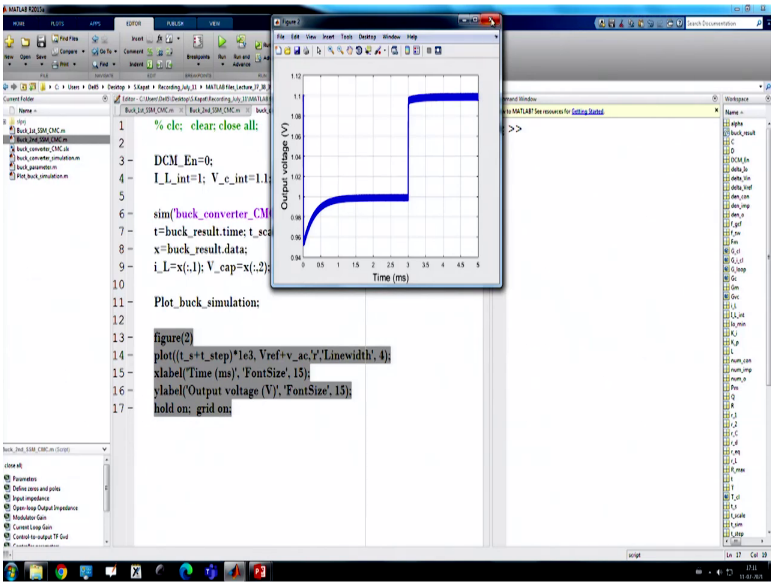

So, we will also run the transient performance and check yeah. So, this is actually ok let us also use uncommon because we want to plot the model one as well ok.

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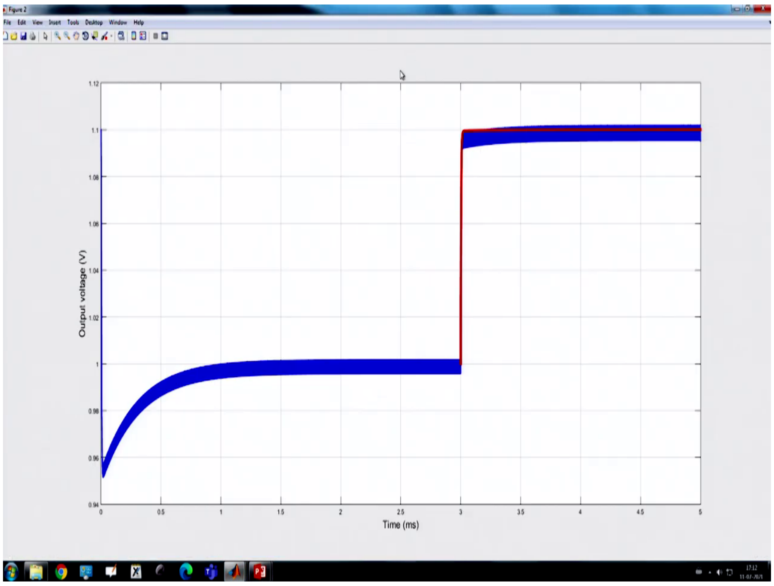

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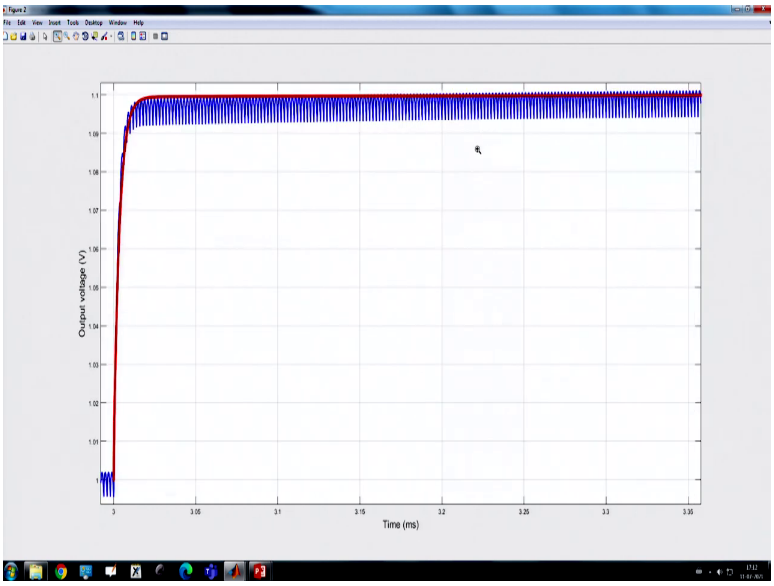

So, if we run it again, it will show that the model is working properly. So, DC mismatch problem is solved because this is a more accurate model ok.

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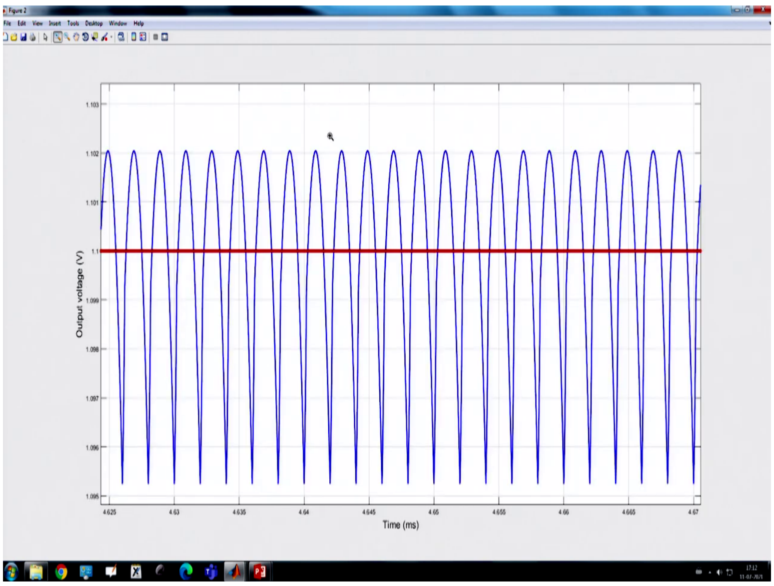

And on top of this, we can also you know plot the response obtained from here; that means they will be almost identical because that we have seen earlier. The only offset problem is solved with the more accurate model; otherwise, they are matching quite nicely, but now what happens if we reduce increase the modulator gain; that means, slope is increasing.

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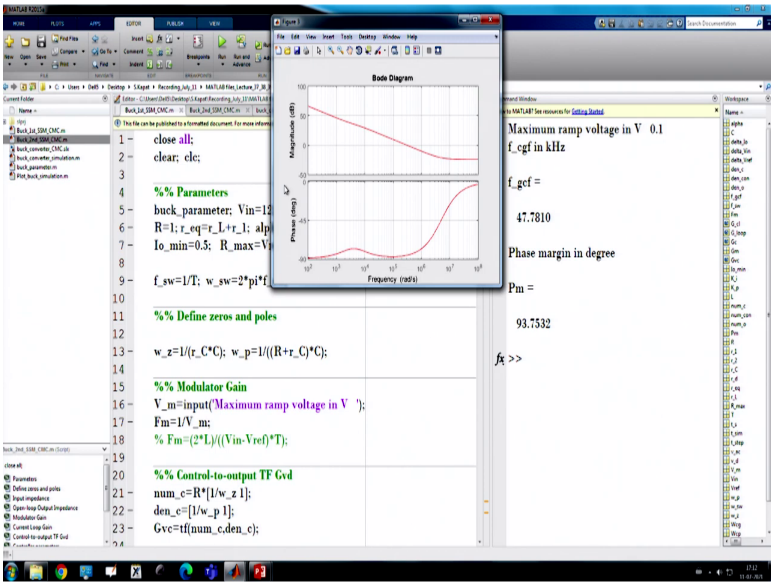

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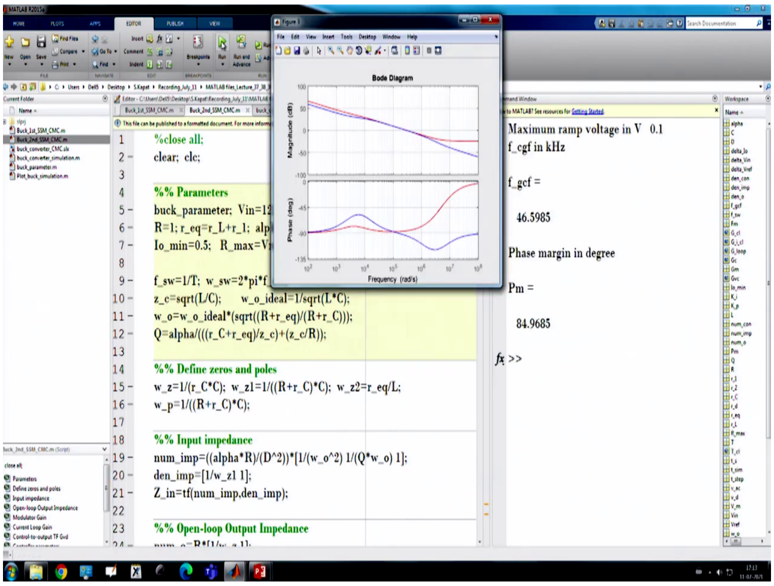

Now, we are running in the same condition. Let us say 0 point 1. Now, the slope of the ramp compensator is point; that means, not slope. I think the voltage earlier it was 0.001 1 millivolt now we are using 100 millivolt which is still low, but we want to see whether the model matches or not 0.1.

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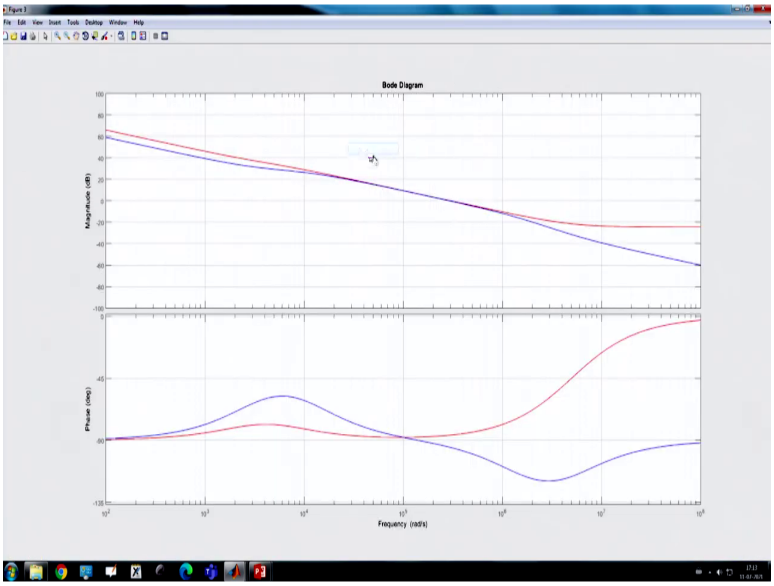

You see the model start deviating ok.

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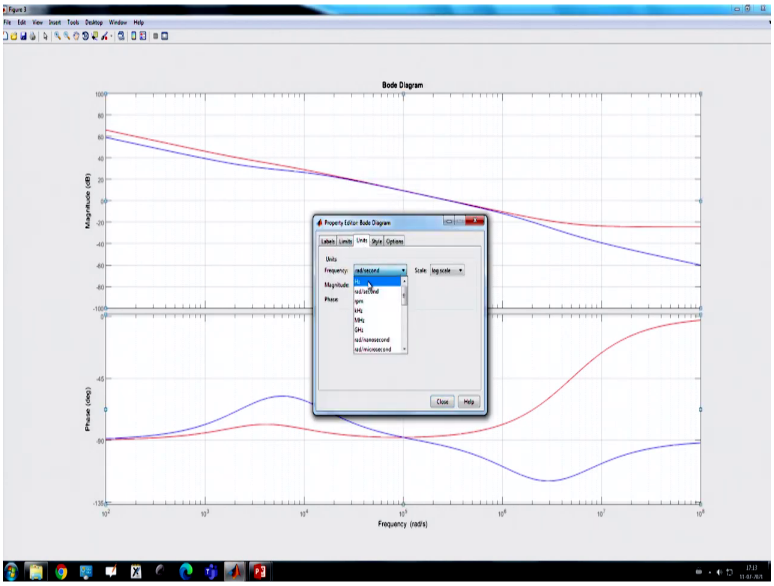

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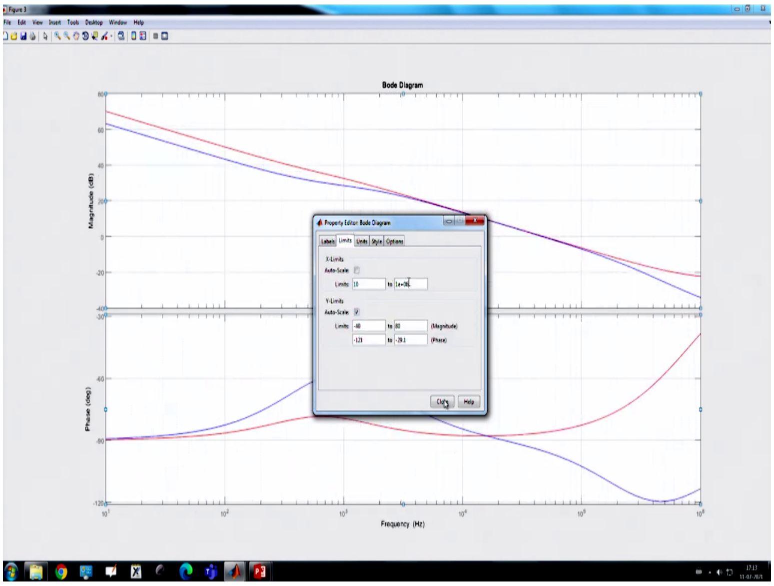

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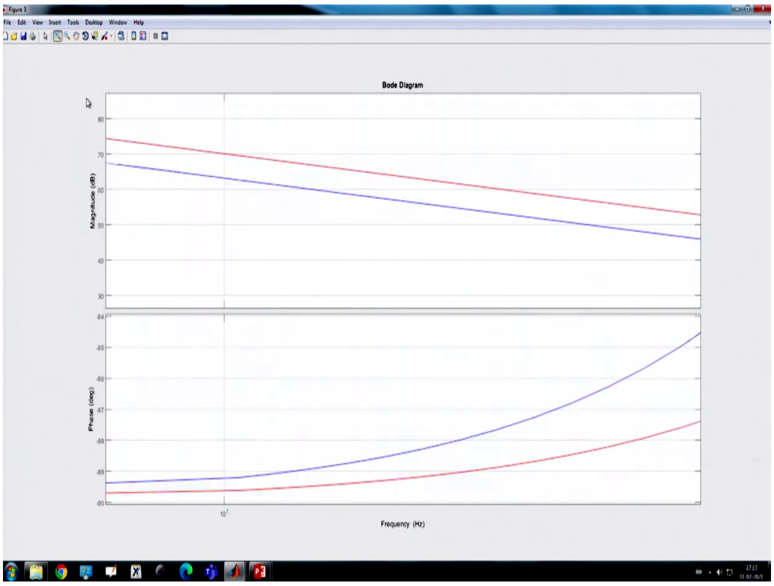

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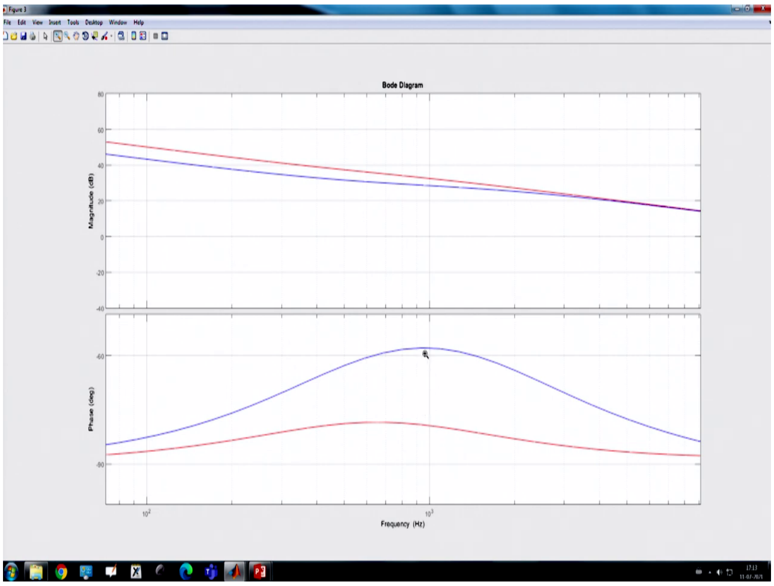

So, if I take the limit because our this is our switching frequency. So, because of current loop gain is now start falling and they are not exactly identical particularly you will see the model which is the first the improved model provide more phase almost there is around 20 to 30 degree and around roughly 10 20 degree phase boost using the improved model.

So that means the accurate model is not exactly the same as the first-order model. So that means whenever the modulator is considered; that means, if you consider a ramp compensation, then the first-order model is not accurate ok. So, we have checked now we can also check the link to output impedance.

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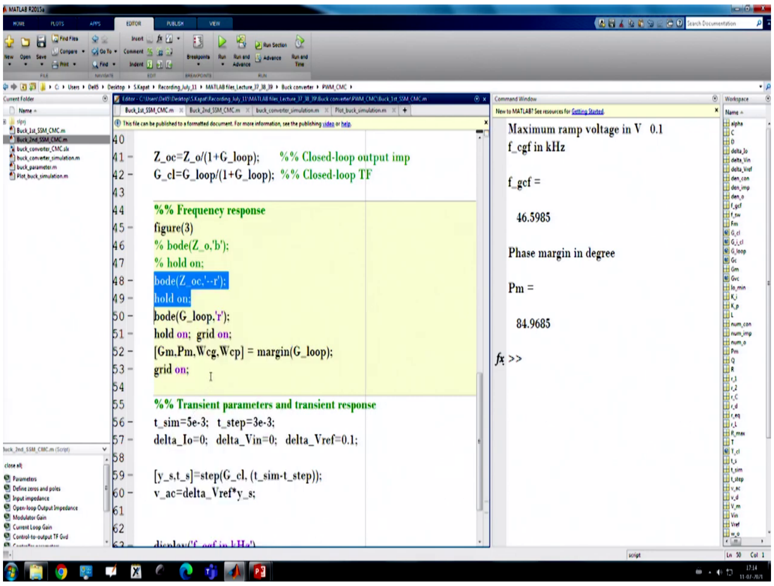

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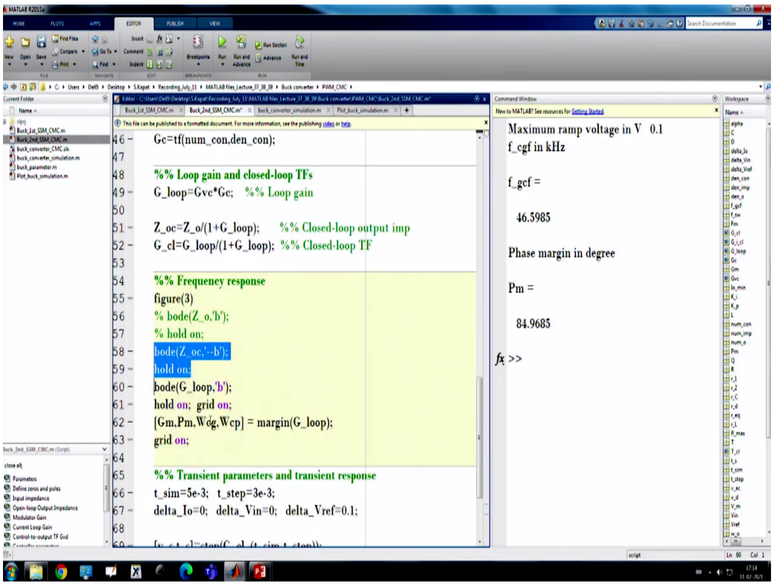

So, we can also check if we want to check the output impedance of these two. Let us check it. So, we can check the output impedance closed loop output impedance can uncomment and we can also check the closed loop output impedance of this ok.

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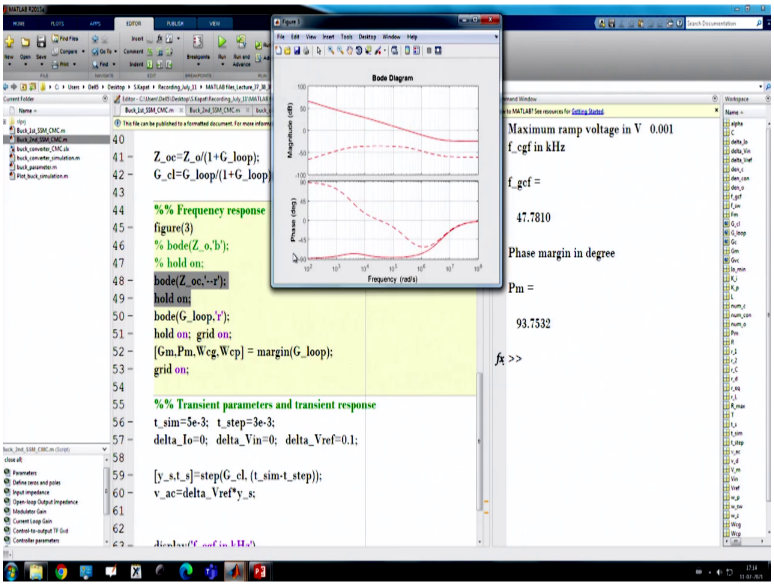

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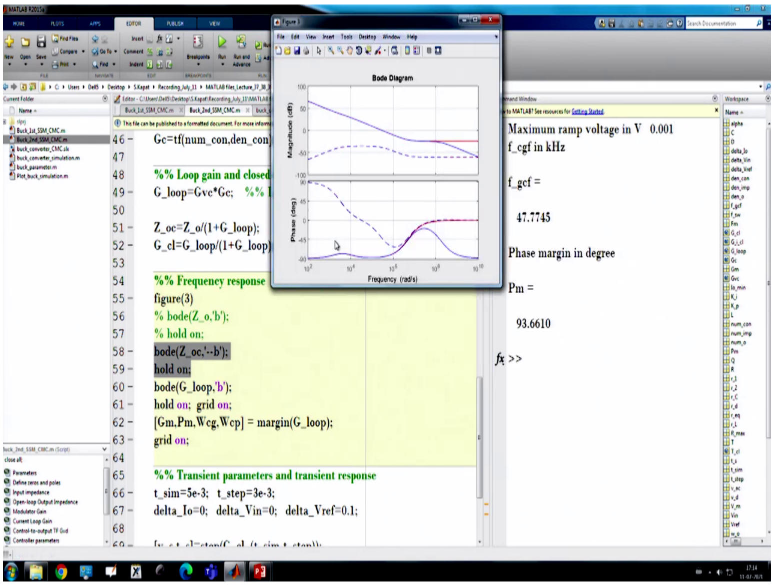

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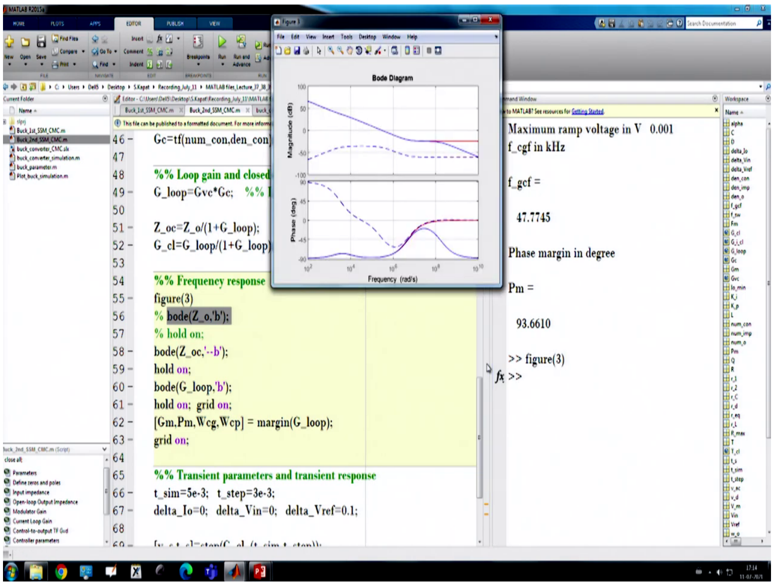

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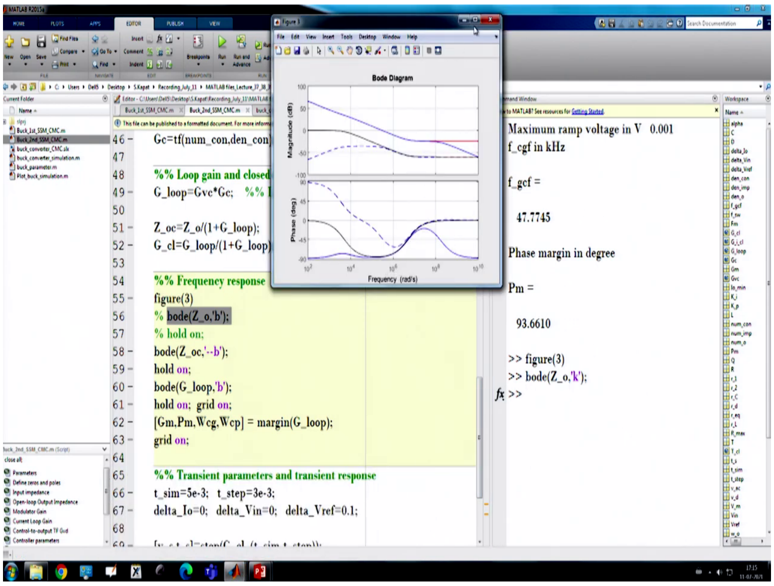

So, when we output impedance and here also ok and now we want to plot along with this you know we want to plot on top of this in figure 3 run to plot Bode the output this is my ok.

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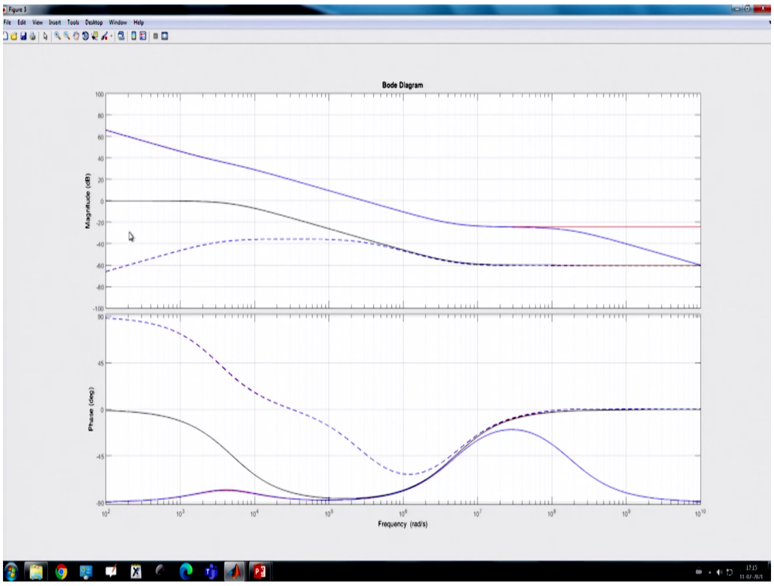

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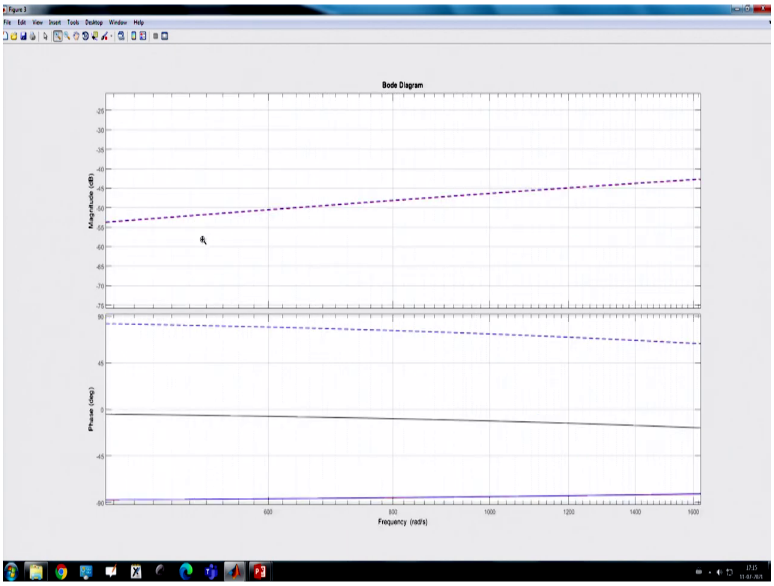

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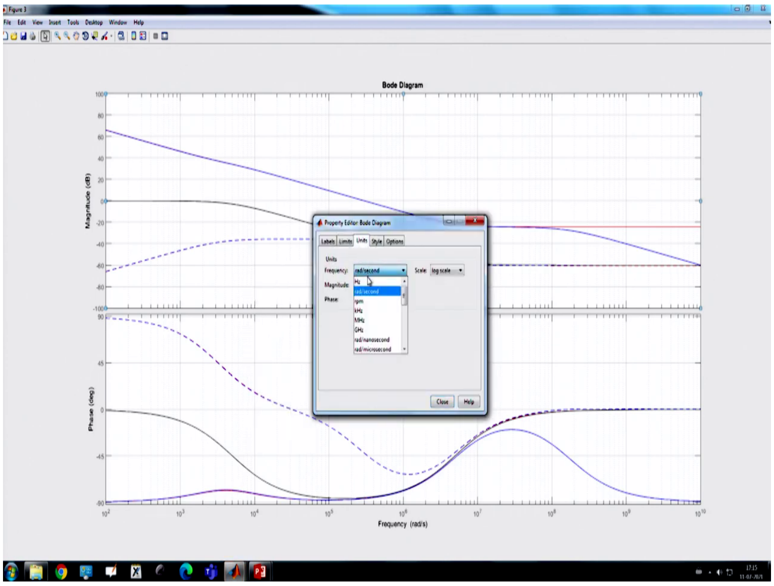

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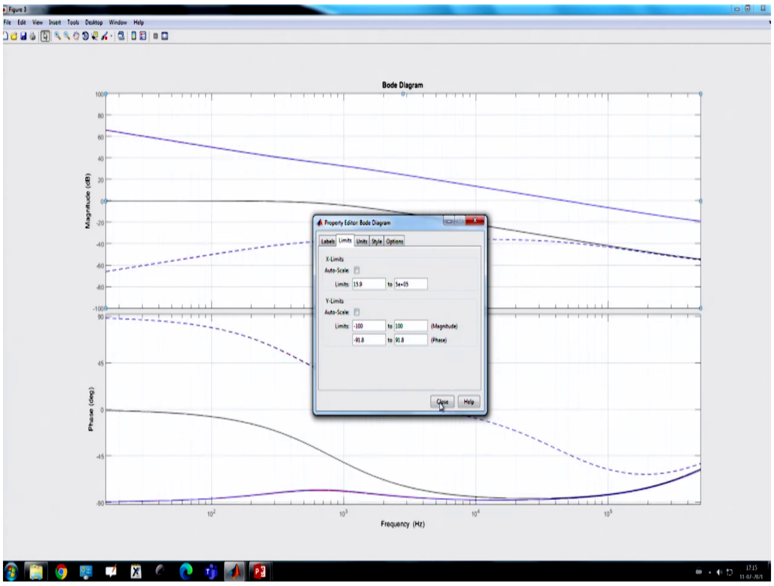

So, this these are my closed loop output impedance because of the outer loop close and at high frequency. So, we have to restrict our switching frequency to should go to radian and hertz then limit to 5e5 yeah.

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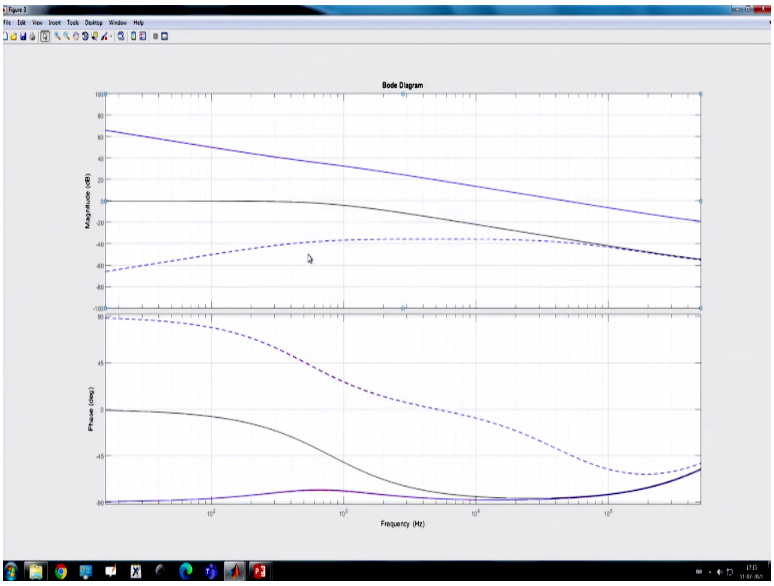

So, they are matching quite accurately this open loop output impedance and that in current mode control this is pretty high at low frequency because it is a load resistance dependent and load lens is 1 ohm. So, it is 0 db and, but using a closed loop, you can reduce that output impedance significantly ok alright.

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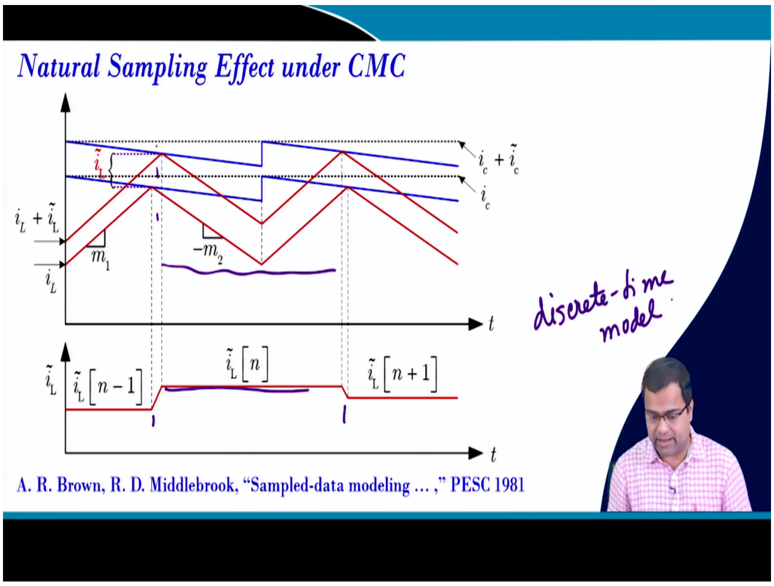

So, like this now current mode control also has a natural sampling effect and this was reported in this space paper 1981 that if you take cycle by cycle and if you take the perturb current, you will find this perturb current will change at every switching transition.

So, that means, any perturbation will remain fixed throughout till this next you know switching even comes and that inherently in you know introduce some kind of sample and hold effect if you take the current dynamics and this effect can be introduced if you take a discrete time model discrete time model. So, discrete time model can be used to capture the sampling effect.

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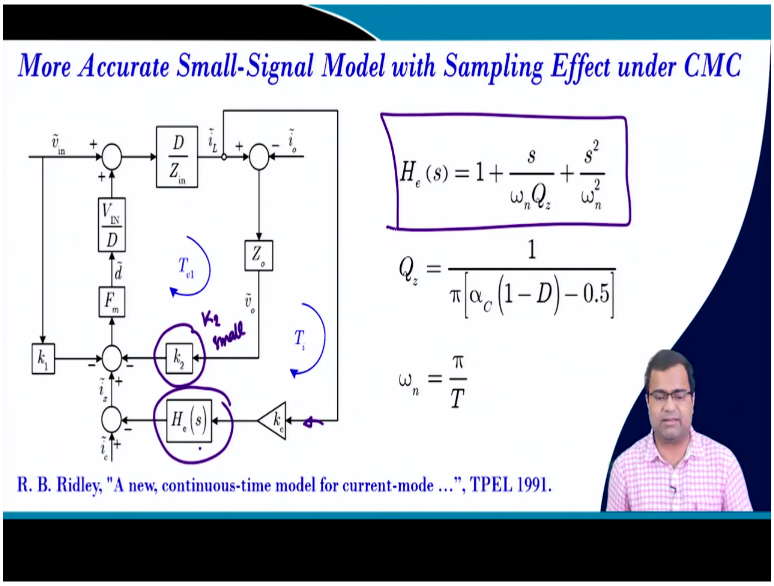

And this sampling natural sampling effect after you know discretization and using continuous time model you know Ridley model actually captures that and that introduces another loop. So, this earlier we have neglected k 2 which was very small, which we have ignored.

Otherwise, this loop will come and we consider current loop right and this H s is coming due to the sampling effect that is the term which was derived from the discrete time model then from conversion from discrete time to continuous time from that the natural sampling effect was captured ok.

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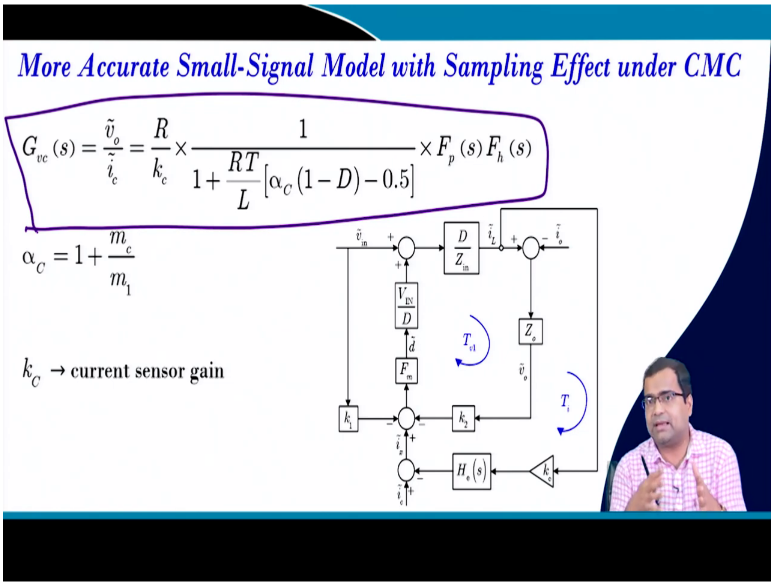

So, this the overall control to output transfer function by including this sampling effect can be derived and in many commercial products actually use this technique. So, that the sampling effect can also be included because that is very important, particularly when you go somewhat close to the higher duty ratio than the sub harmonic. Then other problem will come into the picture, and we have seen also the high current loop gain. There is a significant mismatch.

In fact, the modulator magnitude is also different into the different method and that was one of major research topics in 1980s 90s time when you know the researcher was trying to find out the accurate modulator gain for the current loop gain at the same time and to incorporate the sampling effect.

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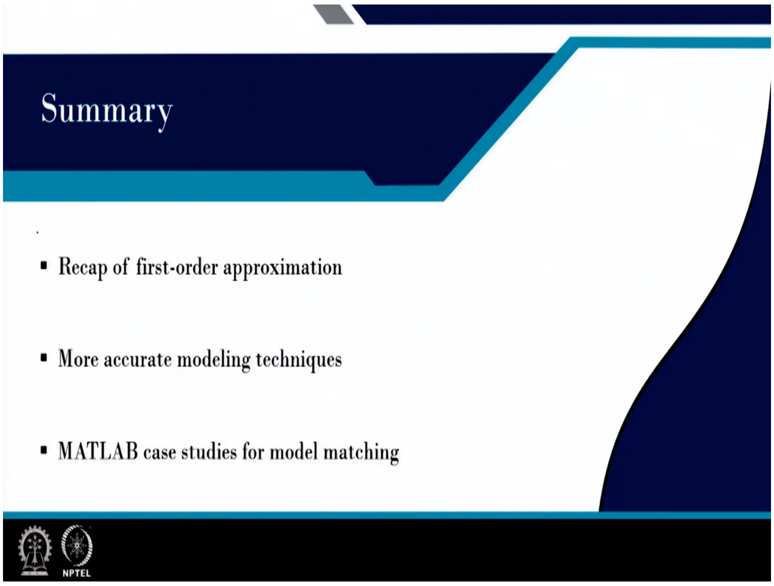

So, with this you know in this course we have in this particular session we have recap like a first-order model approximate model was discussed more accurate modelling techniques were discussed MATLAB case studies for model matching was also discussed. So, this I want to finish it here.

Thank you very much.