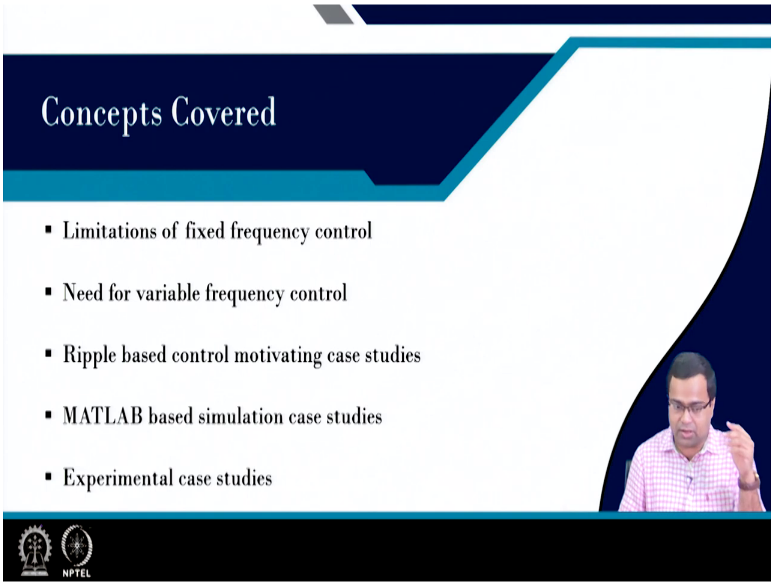
Control and Tuning Methods in Switched Mode Power Converters
Prof. Santanu Kapat
Department of Electrical Engineering
Indian Institute of Technology, Kharagpur

Module - 04
Variable Frequency Control Methods
Lecture - 19
Variable Frequency Control – Understanding Opportunities and Challenges

Welcome this is lecture number 19. In this lecture we are going to talk about Variable Frequency Control. And, we want to understand what are the Opportunities and Challenges using Variable Frequency Control.

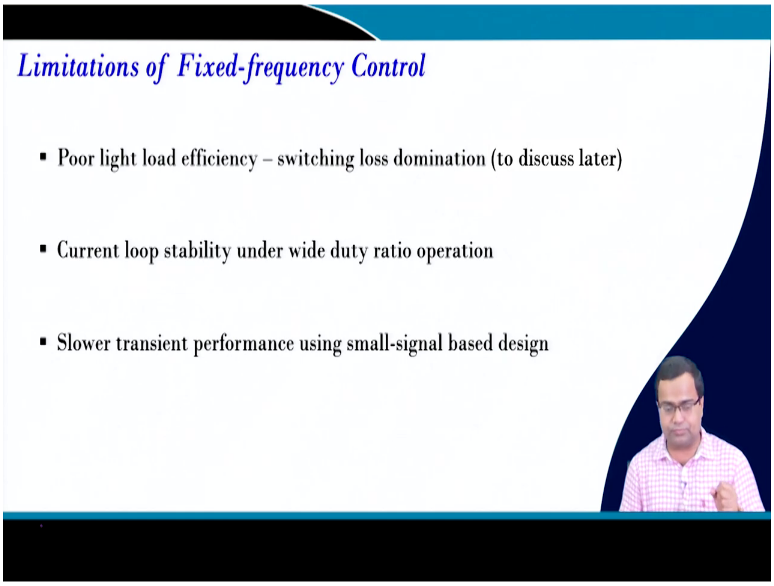
(Refer Slide Time: 00:39)



So, in this lecture we are going to talk about what are the limitation of fixed frequency control, then we will talk about what is the need for variable frequency control. That means we should be motivated to find out why do we need variable frequency control?

Then, we will discuss ripple based control, some motivating case studies, ok. And, then we will also consider some MATLAB based simulation case studies and, of course, few experimental case studies.

(Refer Slide Time: 01:12)



So, first we will talk about, what are the limitation of fixed frequency control. Although, you know point to be noted that is still most of the commercial products, power management commercial product are dominated by fixed frequency control. Particularly you know when you go for high load condition, medium load condition; it is primarily dominated by fixed frequency control.

But, when it comes to light load? That means, when you are talking about a power converter, which has to be designed for a wide load current range. That means, you know the load current can be few milliampere or even in some cases maybe few 100s of micro ampere and it can go up to few 10s of ampere ok.

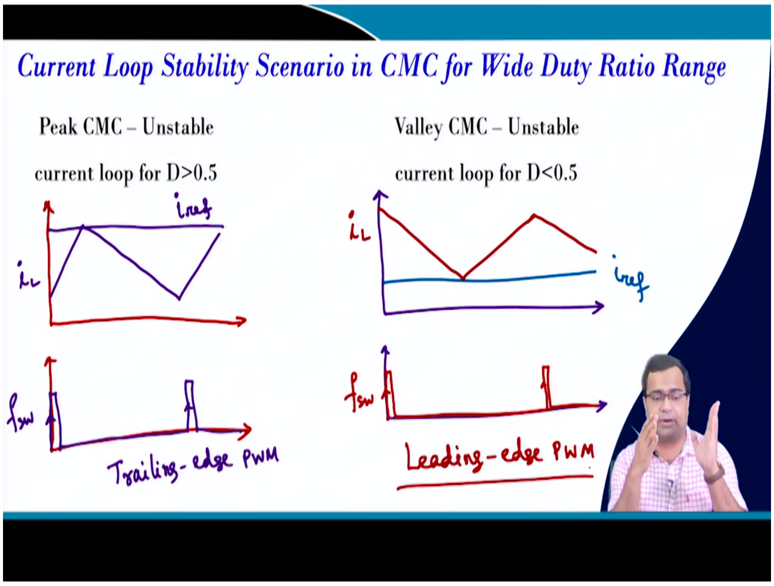
So, in such wide load current range, we will first see that fixed frequency control has a limitation, when you go for light load, when the converter particularly operates in discontinuous conduction mode. Because there we will find the switching loss will be dominated as a result, efficiency can drastically fall. And, when many commercial products go for multimode control; that means, they use some dedicated control during light load and probably they will prefer for fixed frequency control for high load or medium load.

Then, we will talk about current loop stability aspect under wide duty ratio operation. So, we will say the current loop stability can drastically get affected under fixed frequency control and this will motivate us that we will also discuss; that means, in order to overcome the current loop stability problem. We will find out some method to stabilize and then we will see, if we go to variable frequency control, then you can have much you know I would say better degree of freedom in terms of stability of the current loop.

Then, the slower transient performance in the majority of the product commercial products, the design of fixed frequency PWM control, whether it is a voltage mode or current mode, we still use small-signal models. Because we still derive transfer function, we still derive what is the gain crossover frequency, phase crossover frequency, then we design compensator based on transfer function frequency response. And, in future subsequent lecture, whenever we will go for modelling we will see that such small-signal model is not valid when we try to go beyond certain bandwidth.

So, in this lecture we will show some simulation case study that, the response due to a small-signal model and that using actual switching converter, they will start diverging when your you know critical. Crossover frequency you try to increase or the bandwidth you try to increase. So, here the slower transient performance is because of using small signal based design, in fixed frequency control.

(Refer Slide Time: 04:11)



So, now we talk about current loop stability scenario using current mode control for a wide duty ratio range. So, first of all we have two solutions; the first is the peak current mode control. So, how does it look like? Let us consider you know ok; let us consider peak current mode control the waveform control waveform. So, here we are going to consider the clock and this is the waveform ok.

So, if we take the peak current mode control and this is our clock. So, this is our switching clock. And, this is our switching clock fsw and then this is the waveform ok. So, this is our reference current, peak reference current. This is our inductor current ok.

So, in this control, you know this is also called trailing-edge modulation, trailing-edge PWM, because here the switch turns on at the rising edge of the clock. So, that is why it is called trailing edge modulation ok. But, in this control, it can be shown in fact, we are going to continue in lecture number 23, that this current loop will be unstable when duty ratio is greater than 0.5.

In fact, the overall system can be unstable when you know, when you go for outer closed loop, then it can be unstable even smaller than 0.5; that means, it may be unstable around 0.45 or so, ok. So, that is, this is called peak current mode control. So, this is stable when duty ratio is less than 0.5.

Now, there is another current mode control, which is valley current mode control. So, how does it look like? In valley current mode control if you draw the waveform ok. So, same as if you draw so, we have a switching frequency clock and this on then it is again on like this. So, this is the edge of the switching clock. And, here the reference current. If this is the reference current is let us say this one is my i ref. So, the inductor current starts falling then goes up again. It starts falling like this.

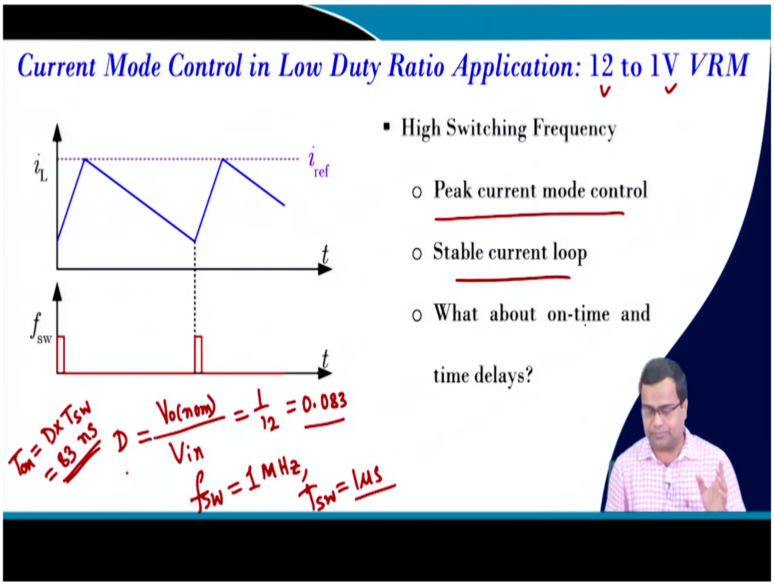
So, this is our valley inductor current ok. So, in this is my inductor current, this is my reference current. So, in this case, it can be shown that the current loop will be unstable for duty ratio less than 0.5; that means, and this is leading edge PWM. Because, here the switch turns off at the rising area of the switching clock and it turns on where the comparator actually reaches; that means, inductor current touches the reference current ok.

So; that means, we have two solutions, peak current mode control and the valley current mode control. Peak current mode control will be useful for low duty ratio operation, because the current loop is stable. And, the valley current mode control can be considered for a high duty ratio operation when it will be stable.

But, if you just interchange; that means, for high duty ratio peak current mode control, then what will be the scenario and the low duty ratio if you go for valley current mode control.

Then, it will be unstable so, how does it look like and how to stabilize that we are going to see.

(Refer Slide Time: 08:14)



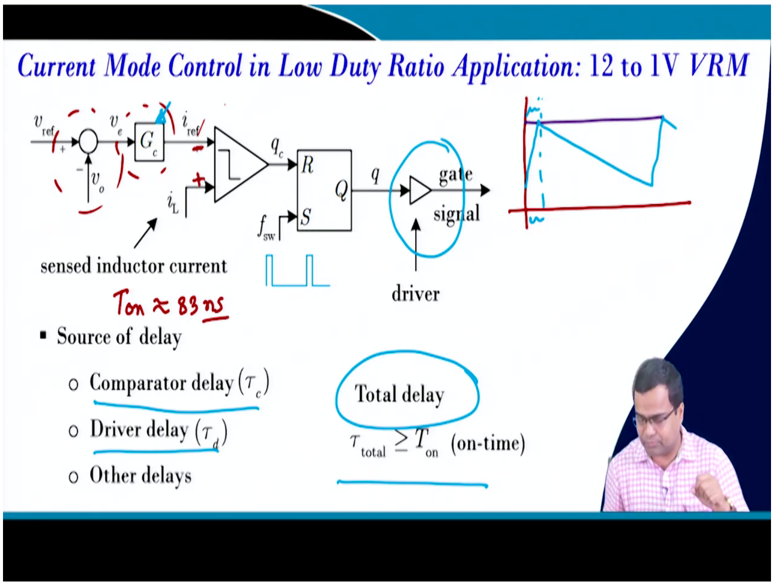
Now, in most of the many applications because we are talking about low voltage high current application, where the input voltage is 12 volt and the output voltage is 1 volt. And, this is typical for the voltage regulator module even for portable application. Where we consider peak current mode control, where we have a current reference and this is the inductor current waveform.

Now, if you are going for high switching frequency, let us say 1 by 12; that means, what is our typical duty ratio t will be 1 by 12, because we know that; we know that ok. So, what is our duty ratio? It is nothing but our V 0 nominal by V in. So, in this condition, like input voltage is 12 volt and output is 1 volt. So, it will be 1 by 12 ok. So, it is roughly around 0.083 ok.

Now, if we go for high switching frequency. Let us say we want to operate FSW to be 1 megahertz, 1 megahertz. Then, what is our switching period? It is 1 microsecond right. Then, what will be our on time? So, our on time will be D into Tsw and in this case it will be roughly 83 nanosecond and this is too small ok; that means, peak current mode control, we saw that stable current loop, but what about on time and delay? That means, for low duty ration operation 83 nanosecond is my total on time ok.

And, during this 83 nanosecond we will see what are the sequence of event that will happen within this 83 nanosecond, whether it is possible to complete all the sequence or not.

(Refer Slide Time: 10:18)



So, if we go for peak current mode control, in fact, you know if you consider the outer voltage loop, then we have a current you know controller and here it will be minus it should be plus, because when it hit the peak current, then the comparator become high and it will reset ok. So, in this sense, inductor current, suppose if you are sensing the inductor current.

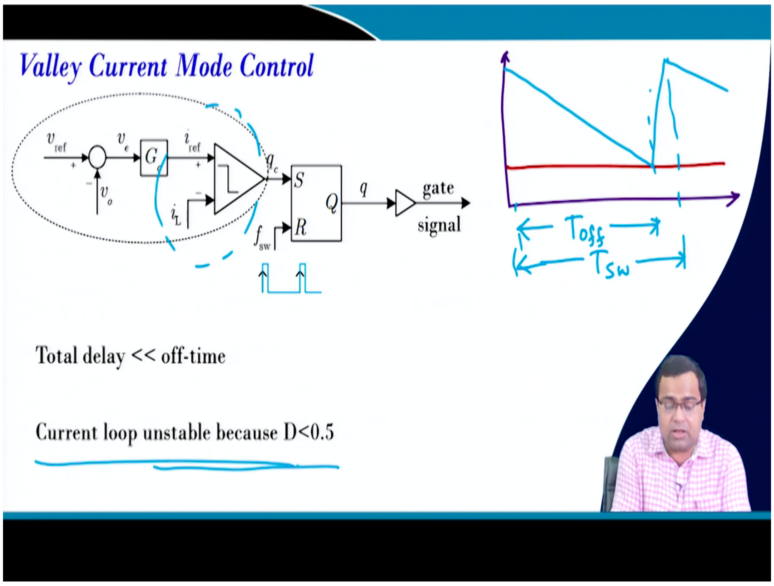
Now, what do we want to discuss here? We saw for this case the on time is around 83 nanosecond for 1 megahertz switching frequency. Imagine what will happen if you go for 10 megahertz switching frequency, then your on time will be 8.3 nanosecond.

So, 83 nanosecond you have to complete this computation, because it is peak current mode control. So; that means, what I am saying that you have you know you have this peak current reference and your inductor current has to reach; that means, the very low duty ratio operation is like this: ok, very low duty ratio operation. So, it is difficult; that means, your comparator has to finish the comparison, then error amplifier has to finish the controller has to finish the computation.

That means, I will say there will be some delay in this; that means, if you consider the delay the sources of delay one is the comparator delay that is a huge delay, the maximum delay, then the driver delay, because this will go to the gate driver which will actually turn on and off the MOSFET. And other delay maybe the delay because of the compensator delay and so on. So, this delay can be total delay can be even larger than the on time.

That means you cannot operate or you cannot implement peak current mode control for low duty ratio operation, because of the constant on the on time the total delay that ratio. That means you have a very little time to compute, then what is the solution; that means, we cannot use any comparator action during the on time. It is simply may not be possible to you know implement.

(Refer Slide Time: 12:23)



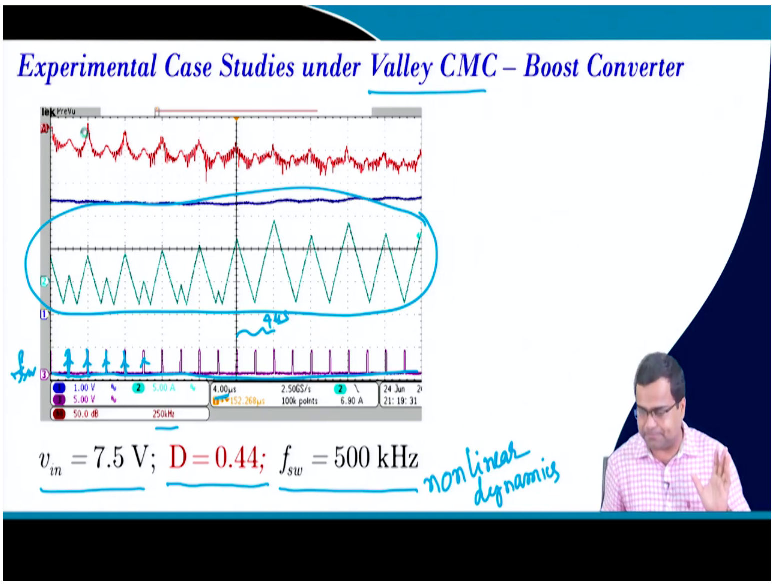
So, what is our solution is a valley current mode control? In valley current mode control you have a long you know time; that means, if you take the waveform ok. Then, this is our valley current reference ok. Now, if you take the inductor current, the inductor current will have a large time like this and suddenly go up, then again go down. That means you have a huge time, the off time is quite large, this is my off time ok.

This is too quite large, and this is my total time; that means, this is my time period switching period ok. So, off time is pretty large compared to the switching period. As a result you will get sufficient time to complete this comparator and other thing, because you have a huge time.

But, what is the; that means, total delay is a much lower than the off time, but the current loop is unstable for D. Because, we have seen that and you will see even you know using some current loop equation, we can show that it is unstable for D greater less than 0.5.

That means, this control technique cannot be implemented, because of low duty ratio operation, because the instability problem, the stability problem current loop stability problem. Even though you put a very high compensating ramp, still you have a problem because that will make the whole system slower ok. Then what is the solution?

(Refer Slide Time: 13:57)



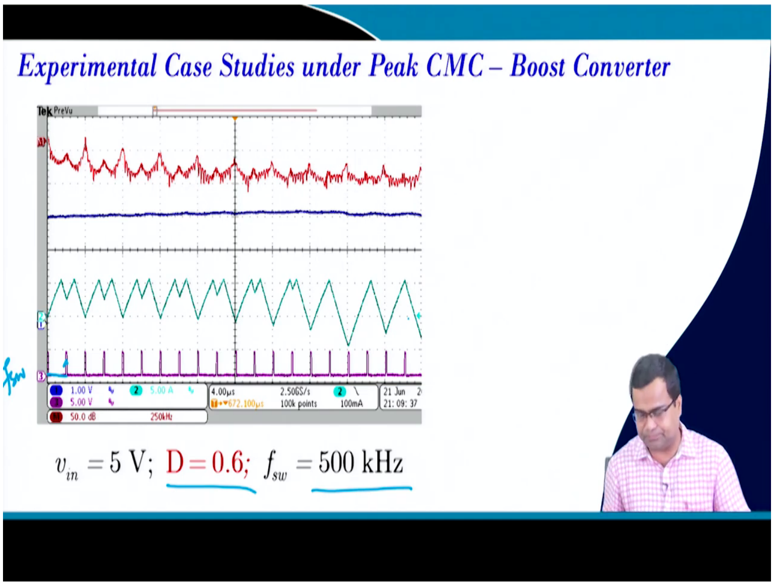
So, I will show you a scenario in a boost converter under valley current mode control, ok. So, under valley current mode control, if a duty ratio is smaller than 0.5, it is just 0.44 and this is an experimental result where the switching frequency is 500 kilohertz, and input voltage is 7.5 volt. So, you will see when you talk about unstable current loop, now our question will come. Then, what does it mean? Unstable current loop means whether the current will go to infinity or it will look something else. So, this is one of the possible scenario.

You see, this is are our switching clock, this is our f sw in the experimental waveform, these are the switching clock ok. So, this comes like this, this is our switching clock and these are the edges; that means, our actual switching frequencies 500 kilohertz, which corresponds to 2 microsecond and you can see that this is the 4 microsecond is a division. So, this division is 4 microsecond ok.

But, actual current waveform does not look like it is operating under 500 kilohertz, because a ripple is quite large. And, this is because of instability of the current loop and this has to be analyse using non-linear dynamics. I mean, it is non-linear dynamic; that means, if the current loop become unstable, then what kind of nature? What is the nature of the current loop? That can be analysed using non linear dynamics so, this is not the part of this course.

But, it is clear from the power spectral, that the current loop because of instability, the ripple current is quite large and it will significantly increase the RMS conduction loss and your efficiency can degrade and also you have subharmonic component content. Because, this is 250 kilohertz is the division. So, you will have a subharmonic component other than the switching frequency; that means, lower frequency and it will make your you know it will create a problem for the input filter design.

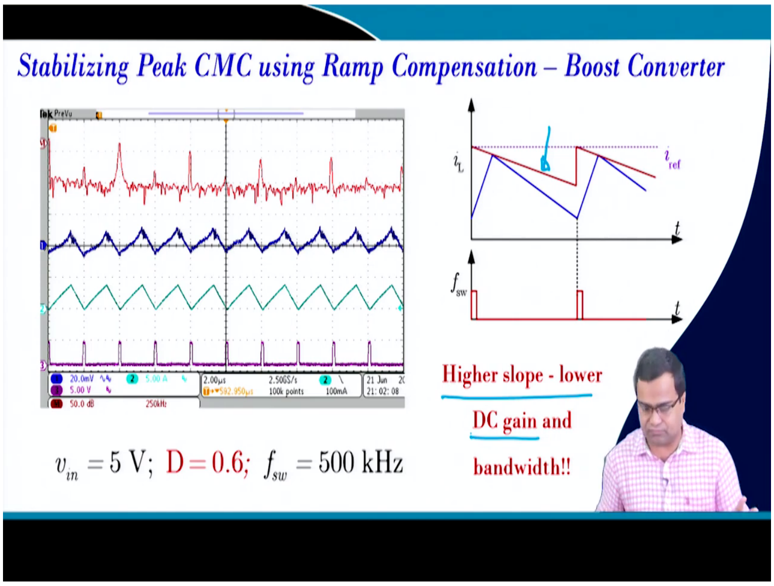
(Refer Slide Time: 16:05)



Similarly, if you take a peak current mode control and if your duty ratio is greater than 0.5 because it is the case just 0.6. And, you see the same problem: the clock is here. It is the switching clock; it is our f sw, and it is of 2 microseconds because the switching frequency is 500 kilohertz ok. And, you will see the waveform of this inductor current does not look like it is repeating in the same frequency of 500 kilohertz. Because it is drastic, it has drastically increased and again this can be analyse using non-linear dynamics, but it is evident that the ripple current is quite large and it will significantly increase the conduction loss.

And, in fact, it will lead actually because of this high current ripple. The output voltage ripple will be significantly large and it will actually go beyond the ripples at the output voltage. Actual ripple will go beyond the ripple specification. So, this is simply not acceptable.

(Refer Slide Time: 17:05)



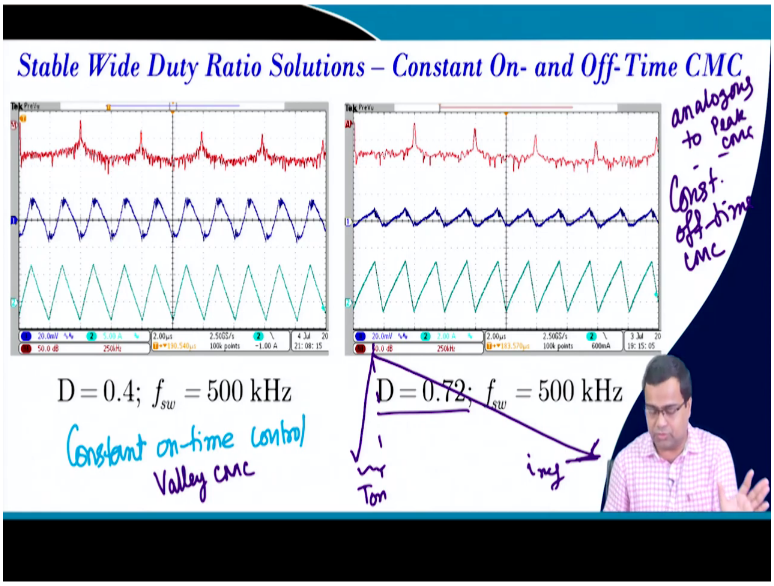
Then, what is the solution? Now, if we add a compensating ramp so, this is our compensating ramp, which is either added with the inductor current or subtracted from the reference current. Then, you can make the whole system stable even for a wide high duty ratio operation.

But, this ramp compensation you know when you go for current mode control we will see, as you add more and more ramp the current loop, whatever benefit will get using current mode control. We are trying to separate the double pole by 2 first order pole by widely separating them. But, once you add more and more compensating ramp, then those 2 poles come too close to each other and it will slowly tend to become like a voltage mode control.

So, the all benefits of current mode control will be lost. So, if you go for a wide duty ratio operation, you need to increase the ramp slope and as a result the major benefit or the advantage of current mode control may be lost.

So; that means, even if we introduce this ramp, this will also reduce the DC gain and we will go when you go to current mode control. As a result, the DC gain will be decreased. So, the closed-loop bandwidth will get reduced ok. And, it can also affect the steady state error.

(Refer Slide Time: 18:23)



So, now, we need to find out a solution. So, these are the problem using fixed frequency control, when you go for a wide duty ratio operation. Whether it is a very low duty ratio, whether it is a very high duty ratio, or wide duty ratio. I is a wide duty ratio operation, what is the solution? So, now, this is the constant on time control, this is constant on time control.

And, we have discussed in week 2, in the week 2. What we have discussed that valley current mode. So, this is analogous to valley current mode control, where we are controlling the valley current, but here time period is not constant, here on time is constant. And, we will see in lecture number 23 that in this control, there is no stability problem in the current loop; that means, the current loop will be inherently stable for the wide duty ratio range, there is no problem. So; that means you can use this technique for a wide duty ratio operation.

Now, when coming back to our original problem; that means low duty ratio operation. So, if you want to activate this low duty ratio operation converter. So, you simply use a constant on time control. So, this is like on time. Since this on time is fixed by a timer, you do not need to make any comparator condition; that means, there is no comparator action coming in this duration. So, it is feasible even for a very small on time. So, for high frequency application, this can be used.

Whereas, at this time like when you are talking about the valley current if this is the i ref. So, this valley current we are getting a large off time and then this is sufficient to complete the comparator comparison right. And, then compensator calculation everything is feasible because this is the time is quite large. And, here it makes sure that this table. So, that is why in many commercial products, in fact, there are many commercial products are coming for low duty ratio 12 volt to 1 volt operation.

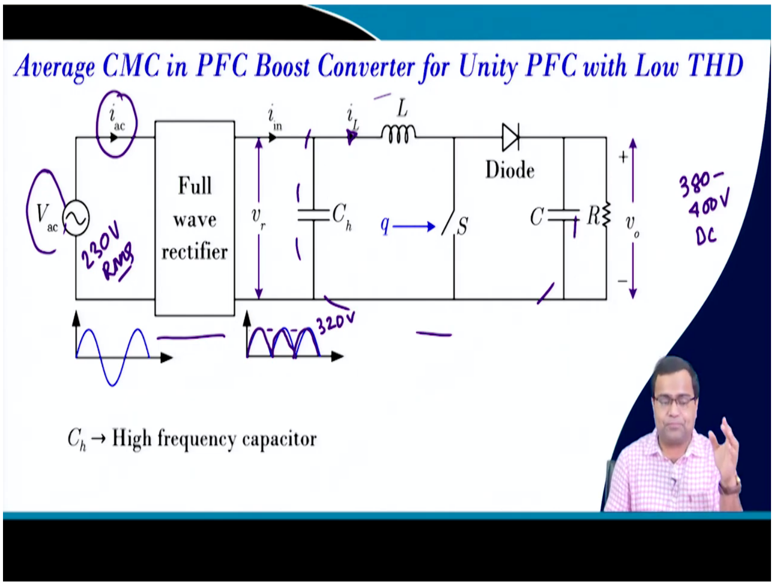
And, also multi phase control, it is slowly system to constant on time current mode control. And, this becomes a very popular control technique for a low duty ratio operation.

If you go for a high duty ratio operation, then you can also implement because you want to operate peak current mode control. Suppose you want to maintain the peak current and this is particularly useful for led driver many commercial products they use led driver using constant off time. And, the constant off time if your duty ratio is higher than entire duty ratio range, the constant off time is also perfectly stable, that we are going to see.

So, you can implement this logic for peak current mode control without any stability problem; that means, we can solve this wide duty ratio operation by using either of this technique. So, this is our constant off time control, constant off time current mode control, this is perfectly stable for the entire duty ratio range.

So, if you whether you want to and this is analogous to, this is analogous to peak current mode control, this is actually peak current mode control, but here our switching frequency is varying. So, off time is fixed in our traditional peak current mode control your time period is fixed ok. That means, this that is why this variable frequency control is very powerful in many commercial products they are coming now ok.

(Refer Slide Time: 22:02)



The next another very attractive solution is the power factor connection boost converter. Because, we need to achieve unity power factor, for full-wave rectifier like particularly this is useful, if you go to you know battery charger application, adapter application, many applications where your input is AC and you need to achieve a regulated output voltage. So, what people use either in a most of the commercial product they use a full-wave rectifier, though now people are shifting towards you know totem pole PFC.

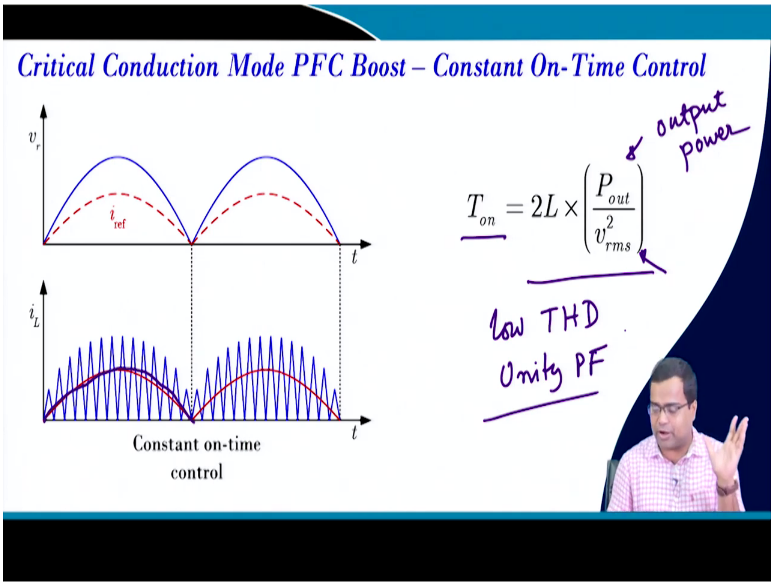
But, here it is a traditional PFC where we have a full-wave rectifier followed by a boost converter. And, here, the objective of the control objective is to maintain the average value of this inductor current in such a way. So, that the input current actually follows the output current; that means there should not be any phase shift so that you can get unity power factor right. So, this boost converter will virtually operate in a way. So, it will look like an equivalent resistive load across the full-wave rectifier.

So, that your input and output input voltage and input current they will be in phase. And, also you need to achieve low total harmonic distortion, because in peak because the duty ratio will widely vary, because your rectified voltage is varying like you know from 0 to this volt. And, you need to boost this voltage from very low voltage close to 0 to a peak voltage. So, this peak voltage in if it is 230 volt RMS, then you can calculate peak voltage which will roughly come around 320 volt ok.

So, this peak voltage and you want to achieve this output voltage roughly 380 to 400 volt DC. So, DC; that means you need a very high step up for a wide range of input voltage variation; that means, duty ratio is varying almost from 0 to 100 percent. And, in such cases you cannot use either a peak current mode or a valley current mode, and many control use traditional average current mode control, again that, there are bandwidth issue, in average current mode control and we will discuss in the subsequent lecture, the loop interaction in average current mode control.

But, if you want to use a high bandwidth stable current control average current control technique.

(Refer Slide Time: 24:23)

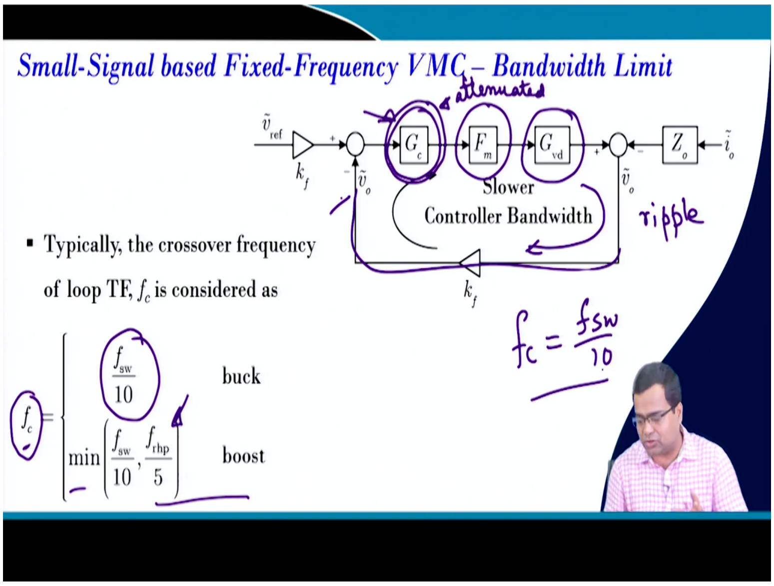


Then, one of the way is to use a constant on time and if you operate in critical conduction mode, then inductor current average can be tracked very perfectly. If you set the on time just twice L by P out, this is the output power, this is the output power and this is the rms voltage of the input. So, if we use this constant on time control using critical conduction mode.

Then you know if you chose this properly even you do not need any other control, just on time this. And, then you can actually achieve very nice like you know unity power factor. And since this control has no stability problem for a wide range of duty ratio. So, you can perfectly you know you can reduce the THD so that means you will get low THD, because there is no distortion due to the current loop instability as well as you will get unity power factor, unity power factor ok.

So, this is a very popular technique constant on time in your PFC boost converter, particularly it can be also applied for continuous conduction mode as well CCM boost and as well as critical conduction mode boost ok. So, this motivates us this variable frequency control is very powerful, even now they are becoming very popular in commercial product.

(Refer Slide Time: 25:48)

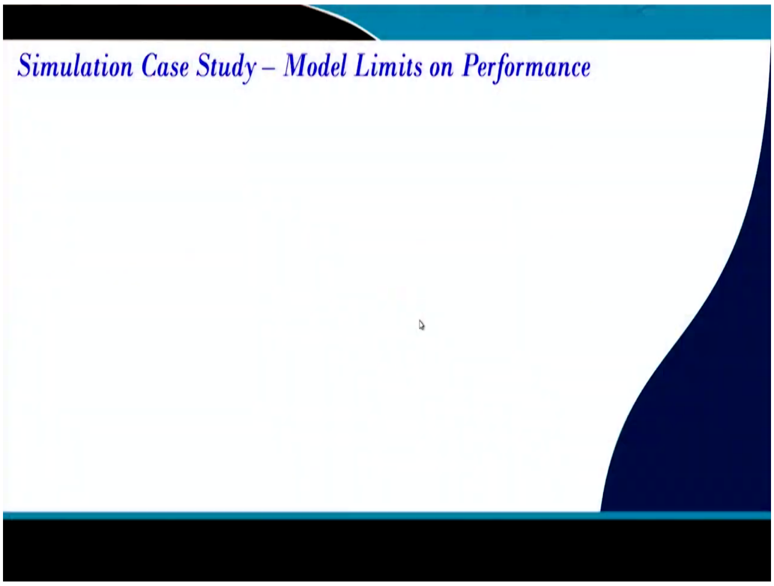


Another aspect that I want to discuss, that in most of the fixed frequency control design. In fact, the design part will come later, but today I want to show you, if you can develop the model of the control to output transfer function and the controller and modulator gain, then if you want to design this compensator.

So, generally our compensators are designed by considering what small-signal model? And, we will discuss in subsequent lecture these small signal models are valid, when the crossover frequency or basically the control bandwidth it said roughly one-tenth of the switching frequency for a buck converter. And, for a boost converter, it is the minimum of f sw by 10 comma right half plane 0 frequency by 5.

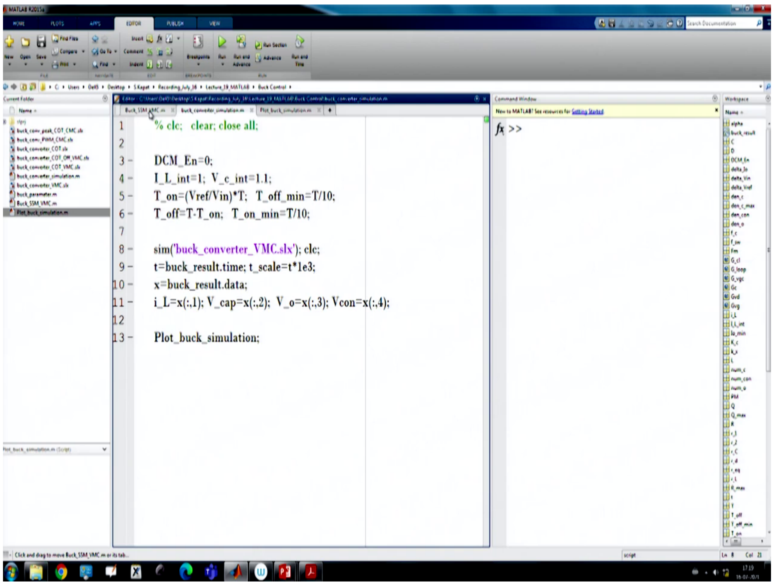
And we will come when you go to the boost converter design under voltage mode; all these will verify using small-signal model as we will as switch simulation. But just to talk about the design of voltage mode control is carried out using transfer function using small-signal model where the model validation the validity of the model poses a constant on the crossover frequency ok.

(Refer Slide Time: 27:07)

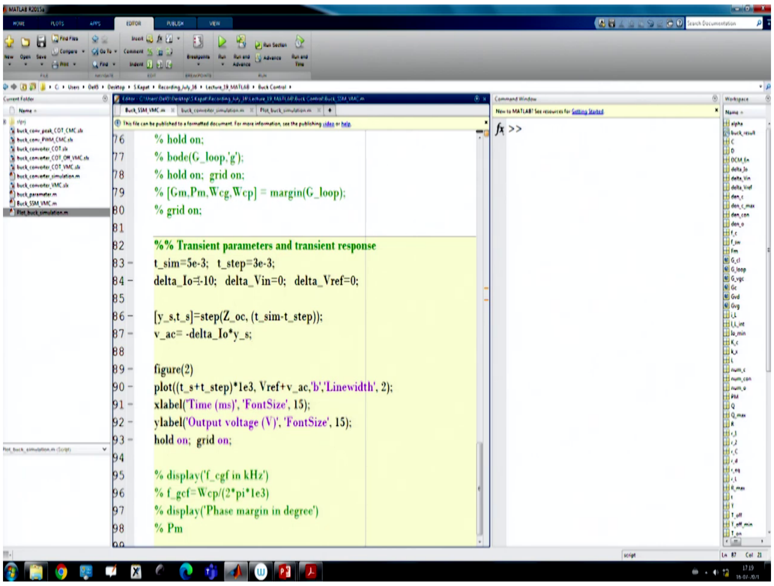


So, now we want to show a simulation case study; that means, what are the model limits.

(Refer Slide Time: 27:13)

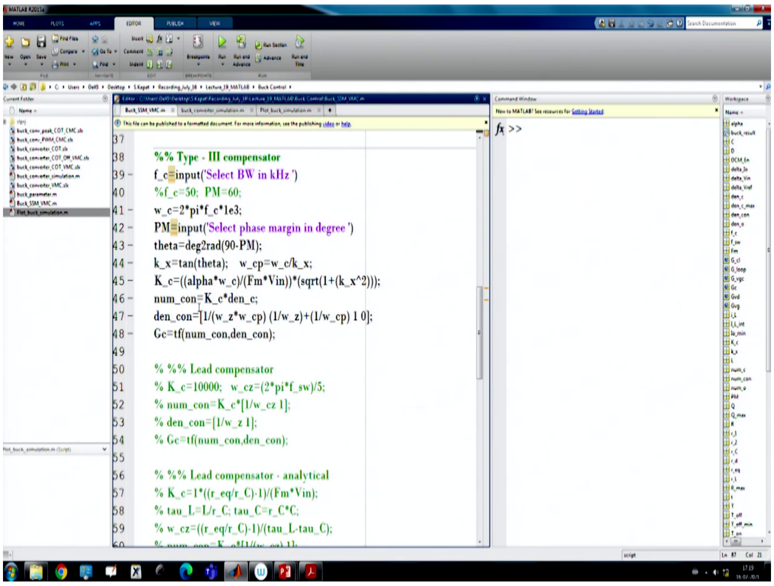


(Refer Slide Time: 27:18)



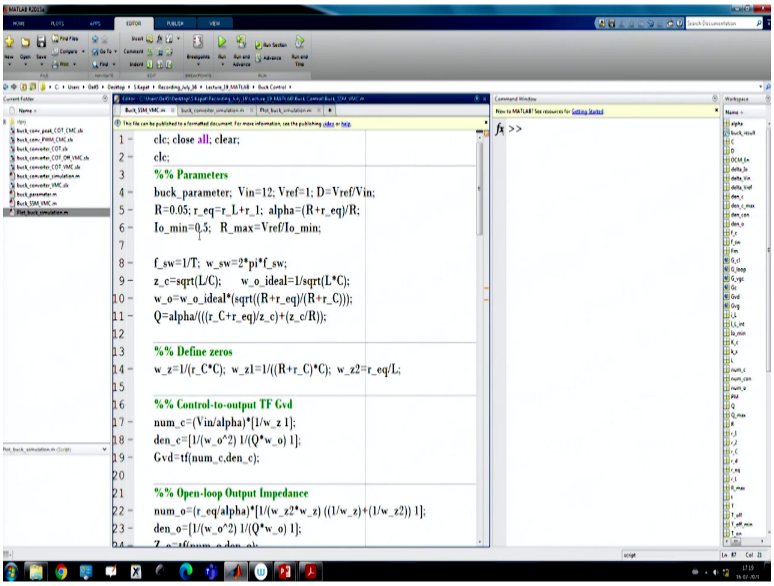
So, let us go to the MATLAB simulation. So, here we want to consider first that we are going to talk about a step down load transient ok, step down load transient.

(Refer Slide Time: 27:26)



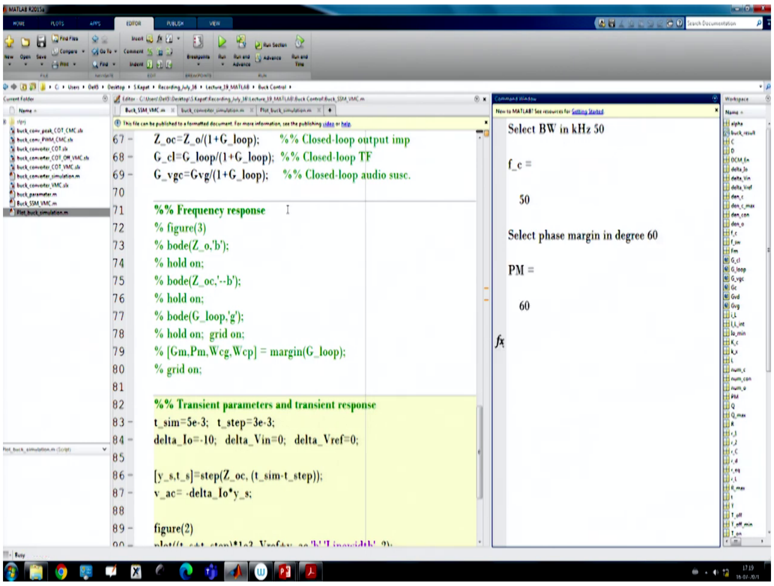
And, I will explain in subsequent lecture all these design criteria MATLAB code.

(Refer Slide Time: 27:36)



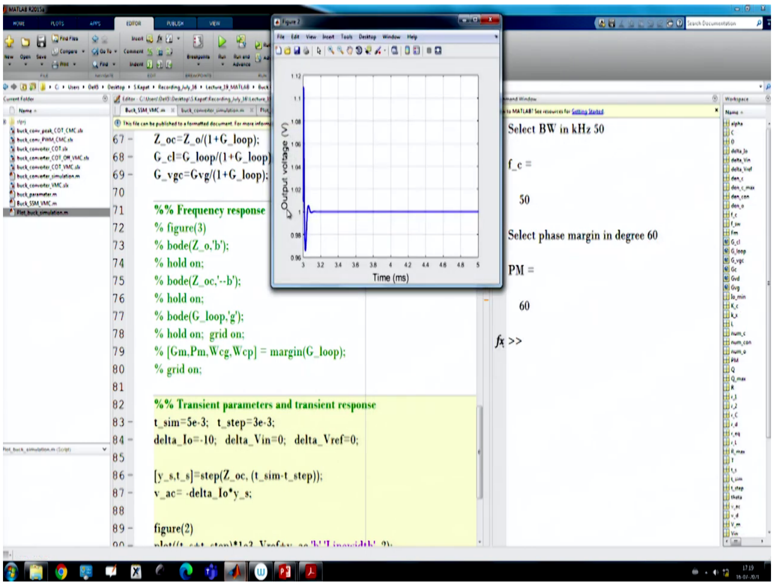
But, for today’s today just for sake of comparison, I am just running this, it is originally the inductor current.

(Refer Slide Time: 27:44)



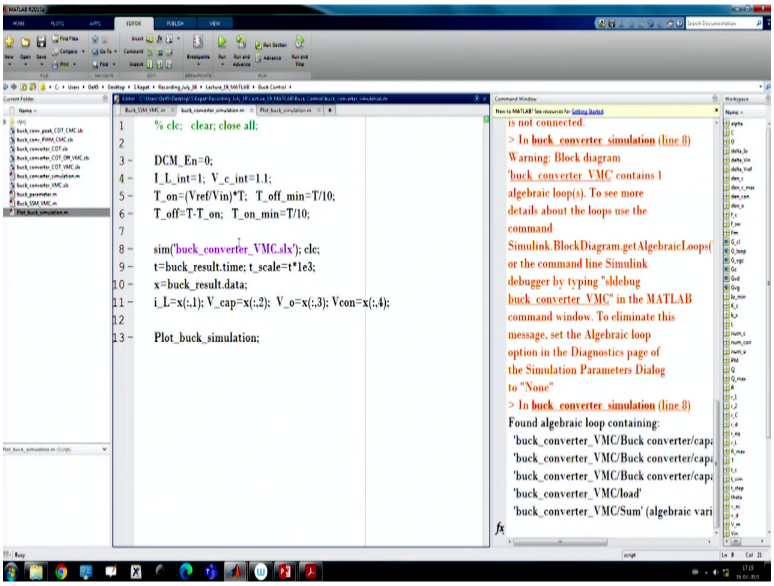
So, is 20 ampere, then it undergoes a load step transient of the step size of minus 10 ampere. So, let us run, here it will ask for the bandwidth. Suppose you set the bandwidth of 50 kilohertz and then in this design it will ask for phase margin 60 DB.

(Refer Slide Time: 27:57)



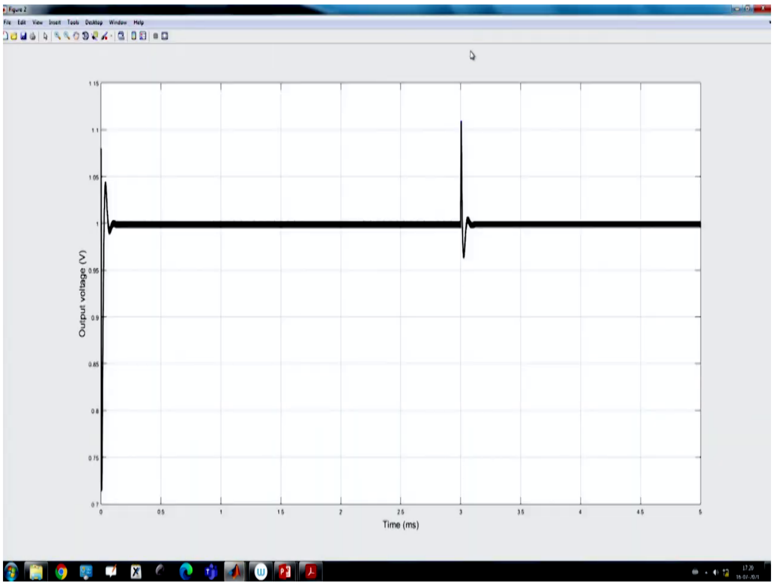
So, sorry 60 degree phase margin, then we want to match this model. So, we want to match this model.

(Refer Slide Time: 28:07)



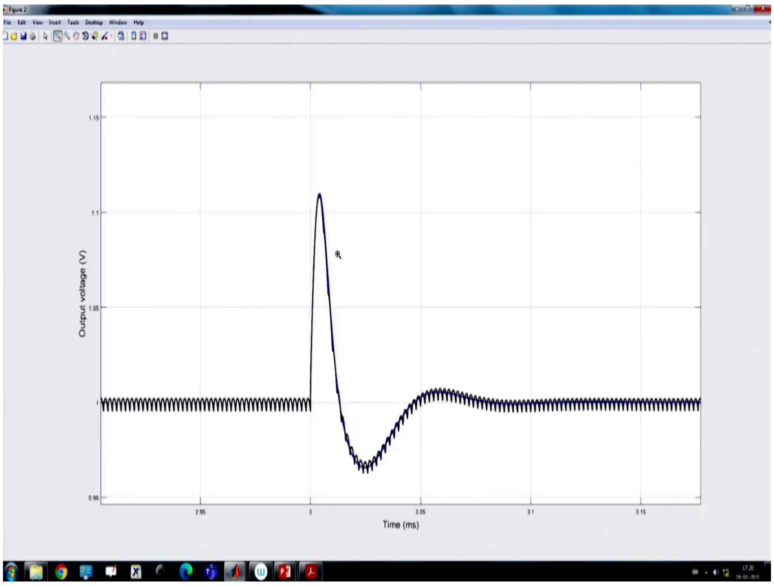
So, we are going to run this simulation.

(Refer Slide Time: 28:10)

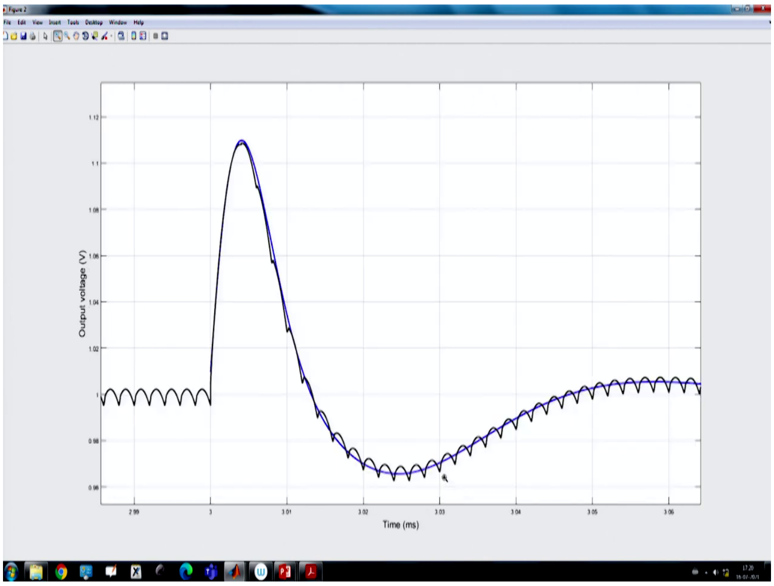


And I want to show you that once you go for this.

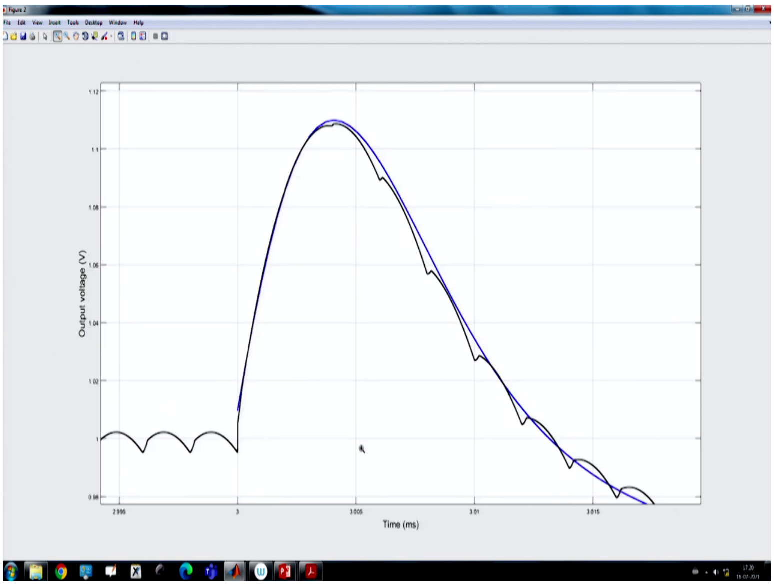
(Refer Slide Time: 28:16)



(Refer Slide Time: 28:18)

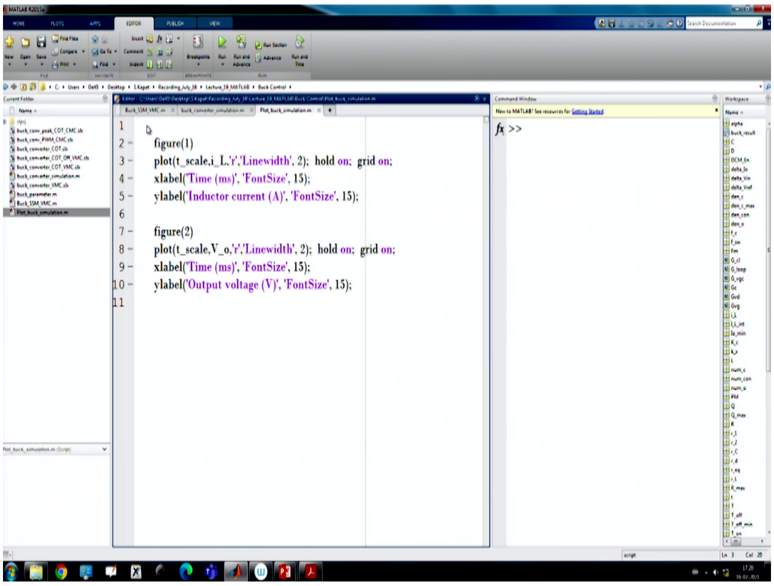


(Refer Slide Time: 28:28)



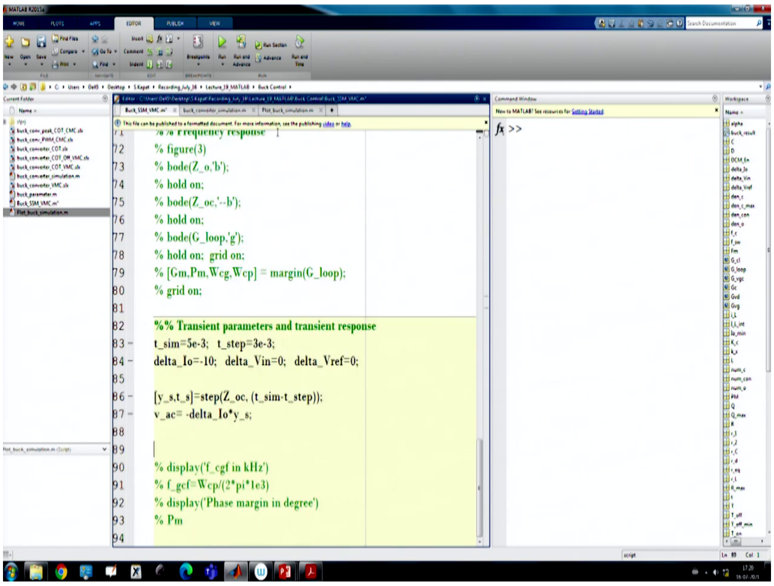
So, you will find the blue color trace ok

(Refer Slide Time: 28:26)

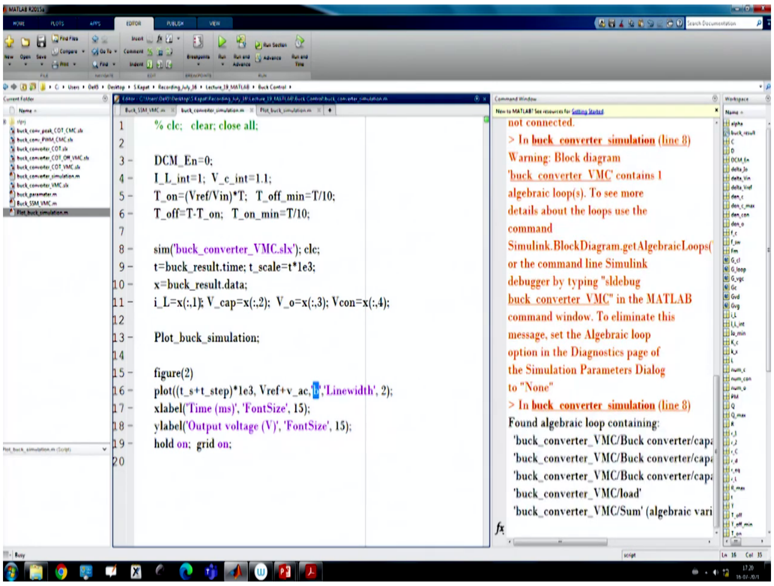


I think we should use a different color, let us use another color, which is a red.

(Refer Slide Time: 28:31)

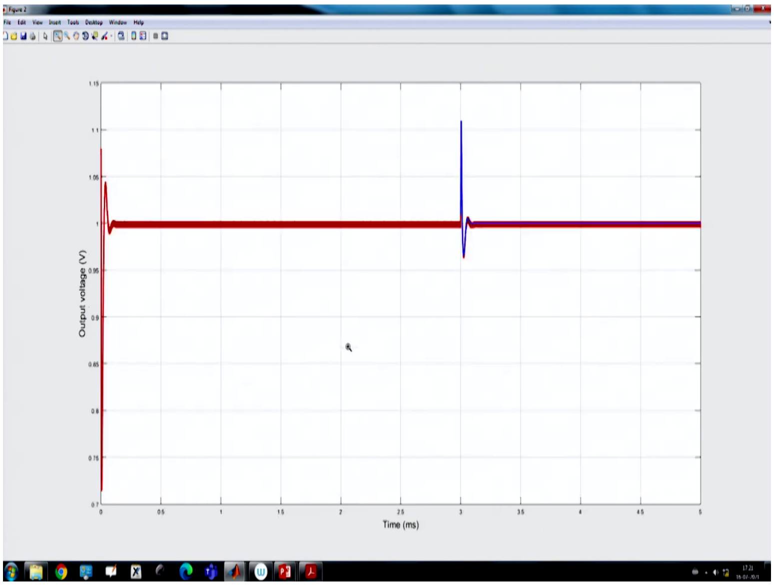


(Refer Slide Time: 28:39)



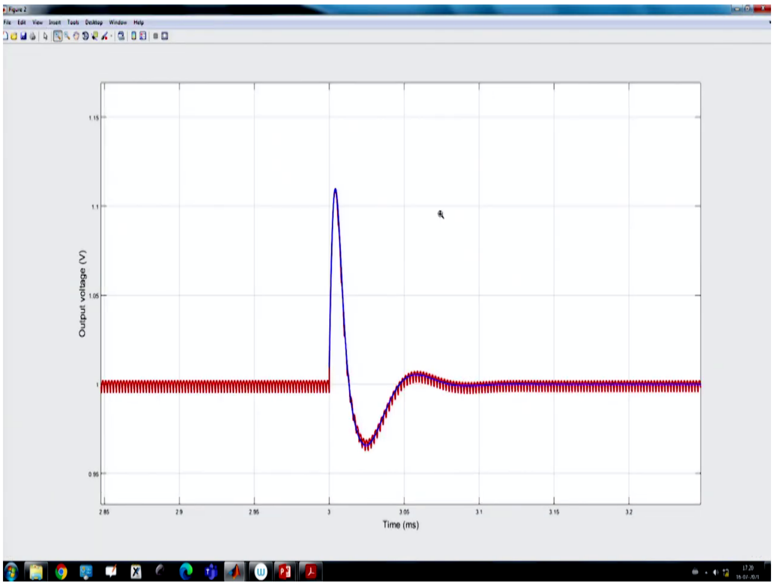
And, we can use this plot command here. So, that you know we can use this plot command here ok. So, it is like blue ok.

(Refer Slide Time: 28:49)

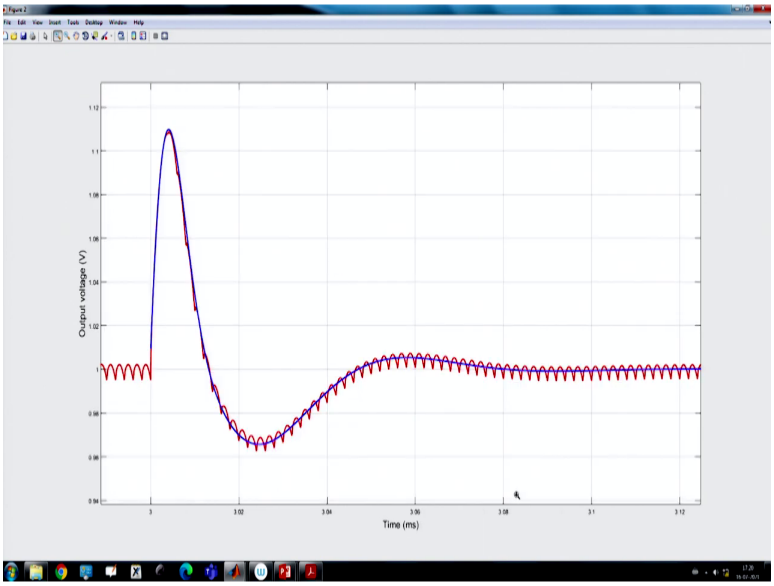


Now, let us run the simulation. So, I want to show you first thing is that ok.

(Refer Slide Time: 28:54)

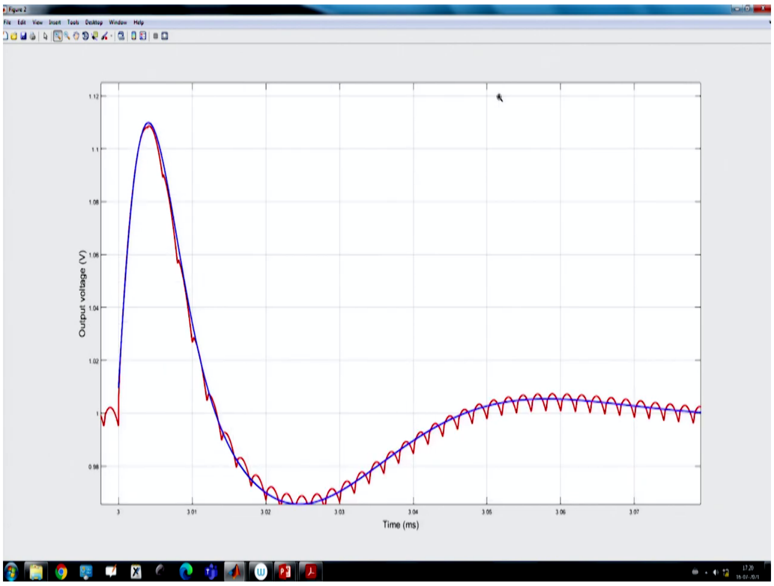


(Refer Slide Time: 28:57)



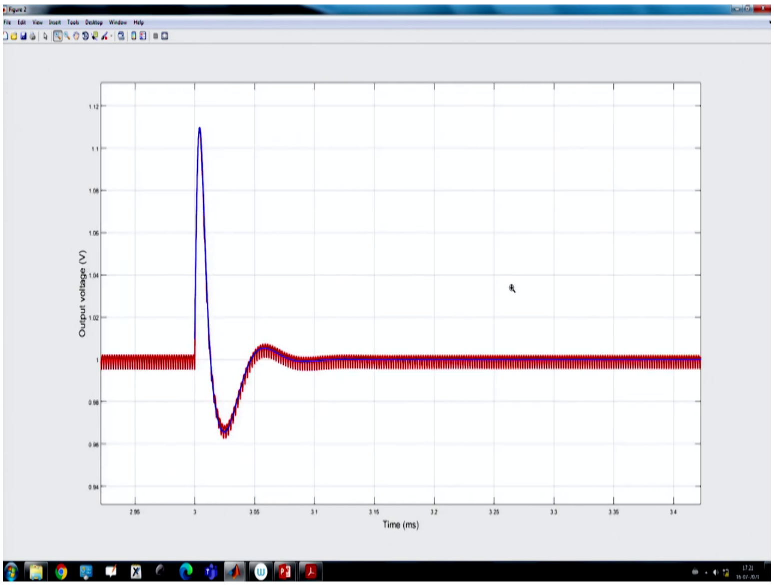
The red one is the actual switch simulation, which is obtained by actual switching converter.

(Refer Slide Time: 29:02)



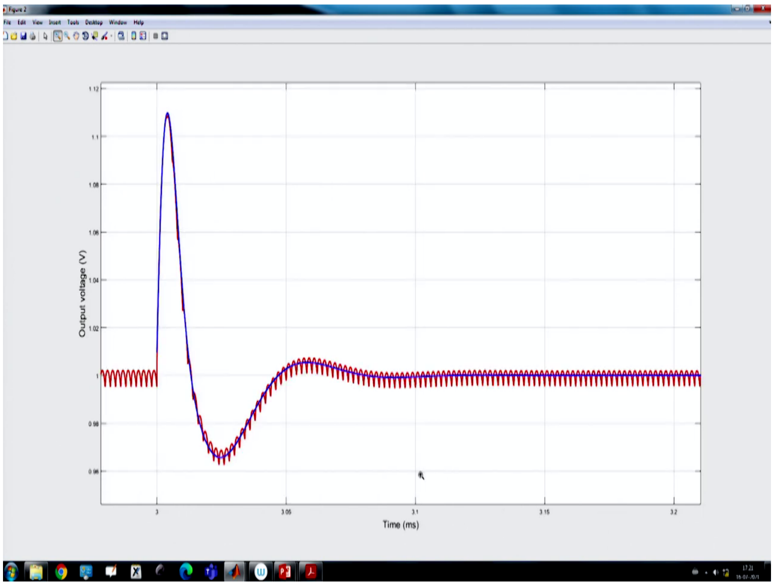
And, the blue one the response we got from small-signal model; that means, this blue signal is coming from small-signal model AC analysis. Then we added offset DC.

(Refer Slide Time: 29:17)

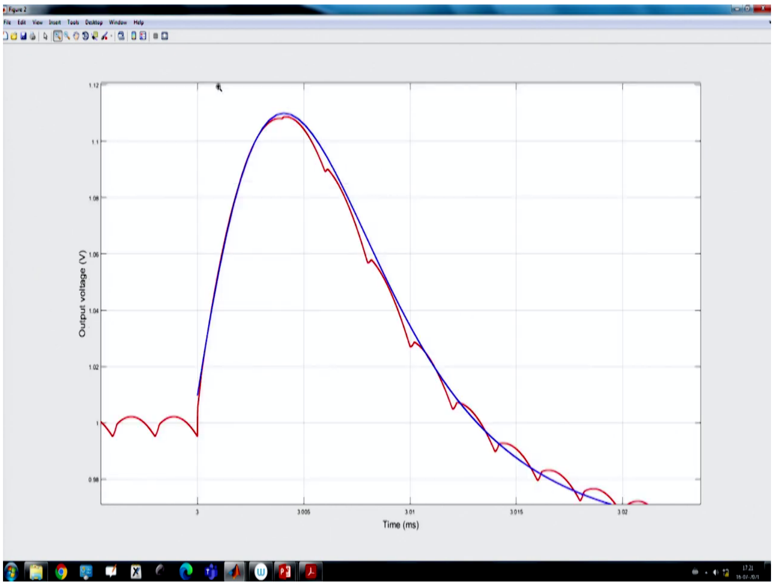


And, now the total simulation result I am showing the model response coming from the small-signal model is accurately captured.

(Refer Slide Time: 29:24)

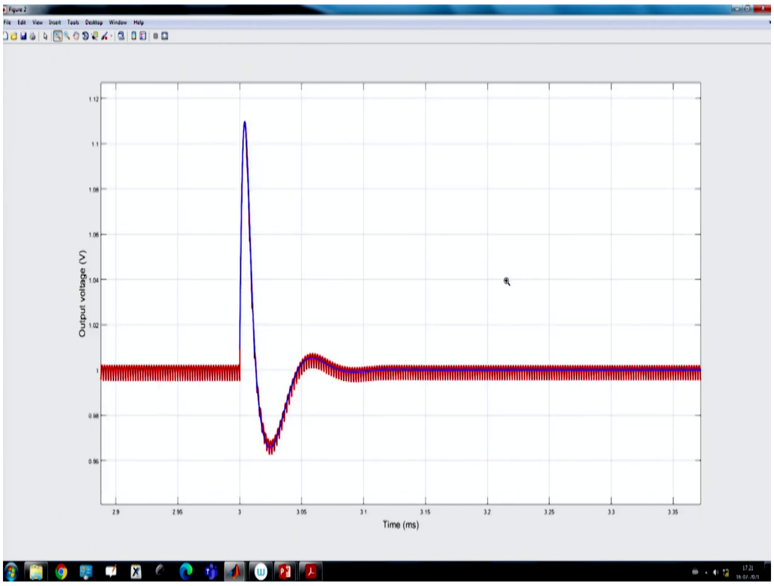


(Refer Slide Time: 29:27)



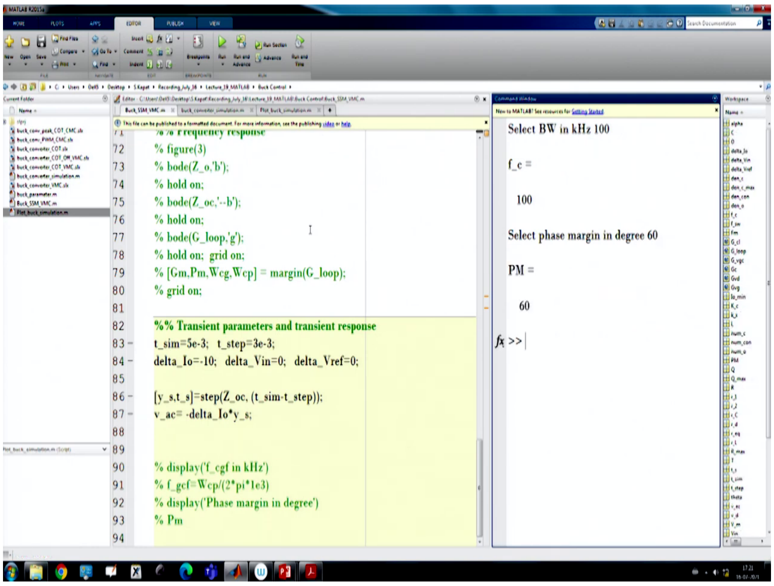
I mean it is capturing the behaviour of the actual switch simulation. If you go, they are more or less capturing the behaviour of the actual switch simulation.

(Refer Slide Time: 29:32)



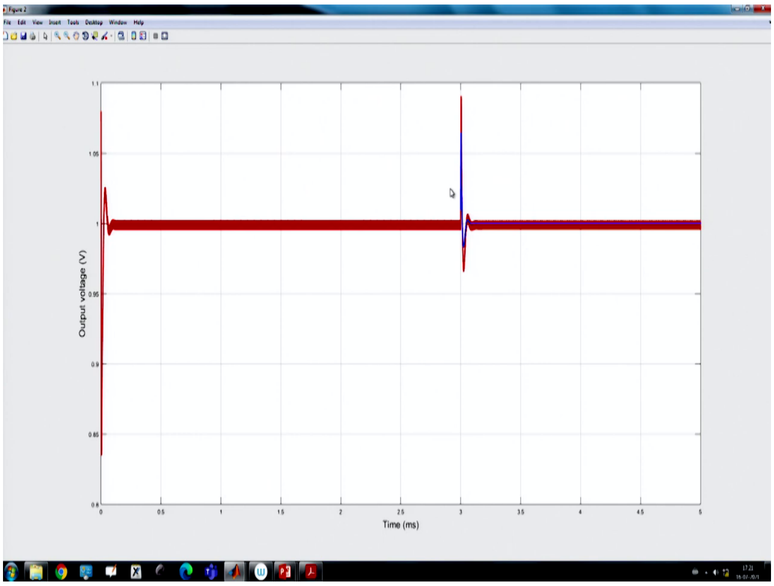
So, you can predict using small-signal model, what will be my overshoot undershoot and so on.

(Refer Slide Time: 29:40)

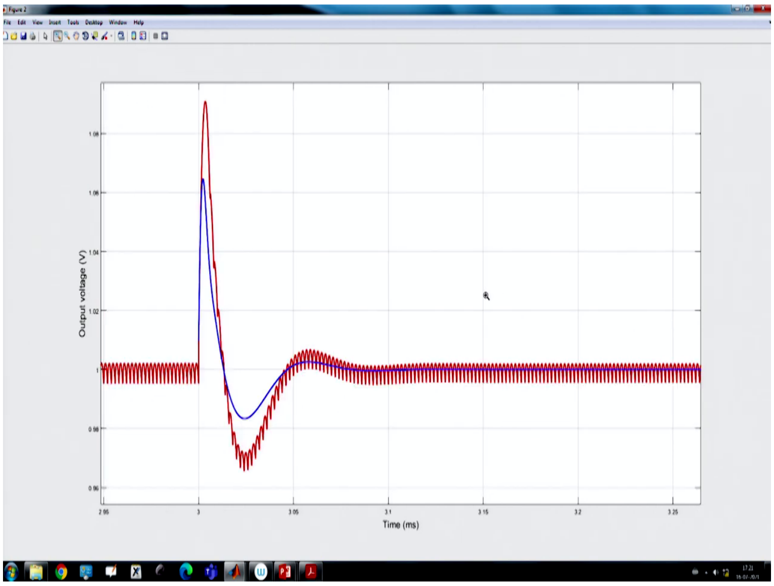


Now, suppose in this case if you want to increase the bandwidth. Let us say we set one-tenth of the switching frequency, suppose, we want to go for one-fifth of the switching frequency. So, 500 kilohertz is my switching frequency, if I go for the crossover frequency is to 100 kilohertz. And, then if we design, if we again run the converter, I want to show you that whether the response can be captured or not.

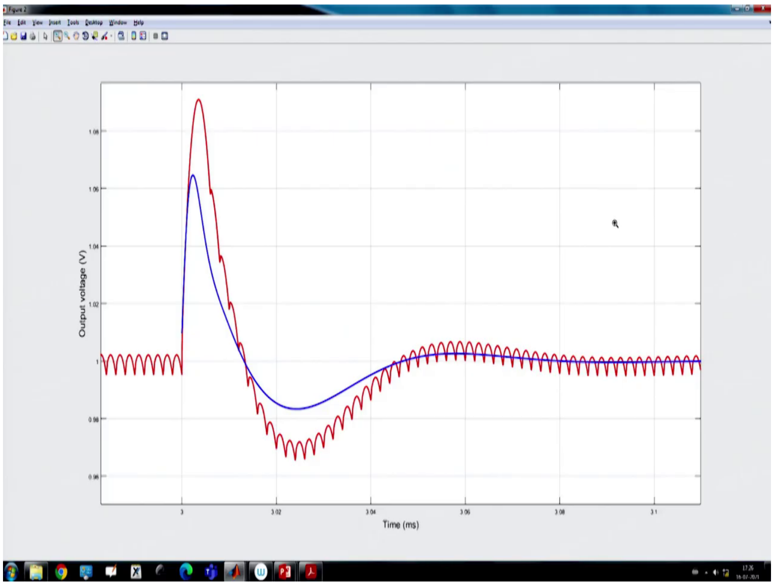
(Refer Slide Time: 30:00)



(Refer Slide Time: 30:05)



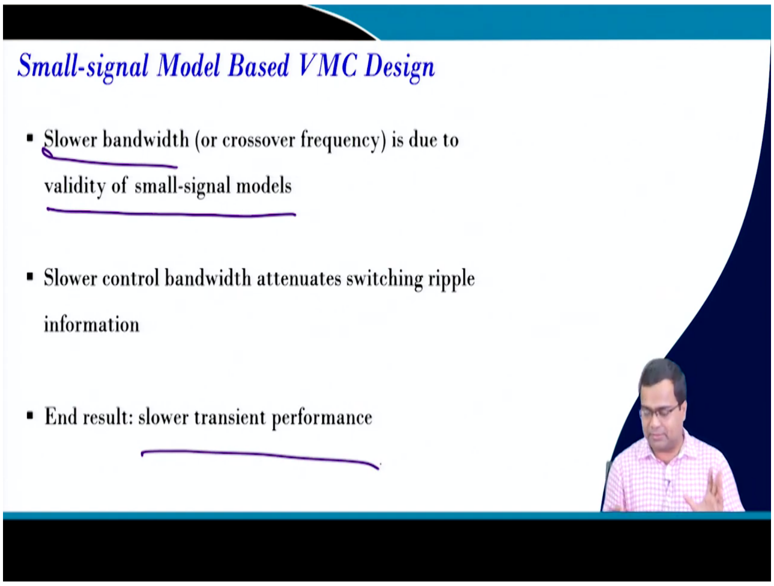
(Refer Slide Time: 30:08)



So, if you check the response, it turns out that your model cannot capture the behaviour of the actual switching converter. That means, there is a significant deviation between the predicted model obtained from small-signal model, which is the blue color and the actual switch simulation coming from the actual DC-DC converter.

That means that is why what we talked about; that means, our original discussion that our model is limited to roughly in one-tenth that is why in most of the commercial product our small-signal model is designed for one-tenth up to one-tenth of the switching frequency. But, it is a switching converter. You can improve the performance, but you should not use a linear model, otherwise you cannot predict.

(Refer Slide Time: 30:49)



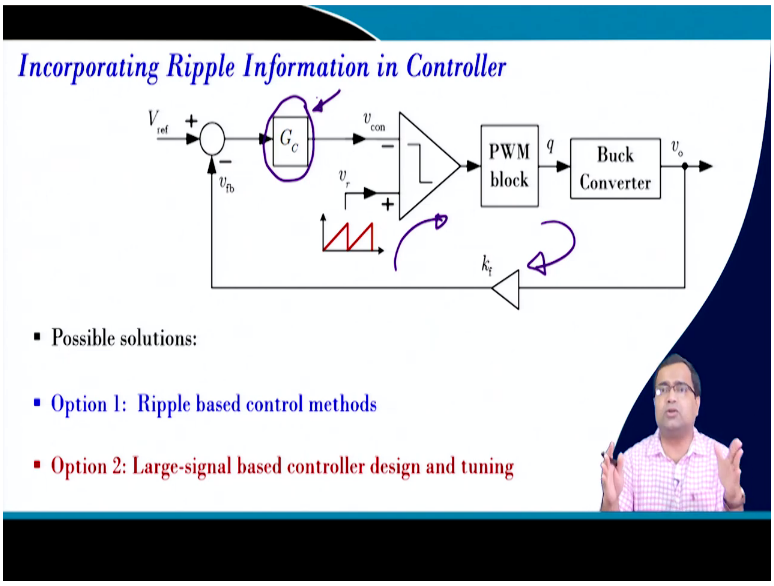
So, we have shown the case study, and we have discussed suppose small signal based voltage mode design ok. And, we identified the model limit ok. Now, what does it mean? That means if you go back, the slower bandwidth is due to the validity of the small-signal model.

That means, whatever bandwidth we are setting in the closed loop, we want to make sure that our model is valid that is why the bandwidth and you know all this frequency response comes into picture, when we can get a linear model right and that is valid for one-tenth of the switching frequency. So, we are getting slower bandwidth ok.

The slower control bandwidth attenuates, that means, since our control bandwidth is slow which is limited to you know control bandwidth is one-tenth of the switching frequency. So, this controller bandwidth is slow and it will try to attenuate the ripple information which is coming from the loop.

That means your actual output voltage you should have some ripple right, some voltage ripple. So, this will be attenuated here; it will be attenuated here. Because your controller will act like a low-pass filter due to you know, because it is bandwidth is small. So that means we are losing the ripple information in the controller and that is why our performance is limited. And the end result is a slower transient performance ok.

(Refer Slide Time: 32:17)

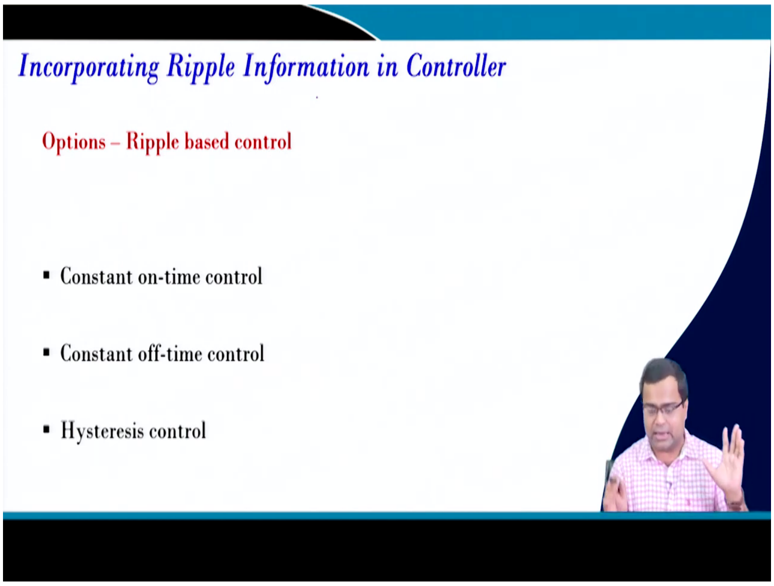


Now, if we want to incorporate the ripple information into the controller, can we improve the transient performance? So that means, what are the solution, because, this was our earlier example I have shown right. So, one of the option is that we go for ripple based control. That means, in the control method, we want to inherently retain the ripple information of the output voltage ok.

And, another approach will also show some result test cases is a large single based designed. We still can continue the pulse width modulation technique voltage mode control, no variable frequency control, but in the process of controller design, we incorporate ripple information. That means we are not making this controller or the bandwidth slower, because there is no bandwidth concept, because here we want to take the nonlinear model where we want to retain the ripple information.

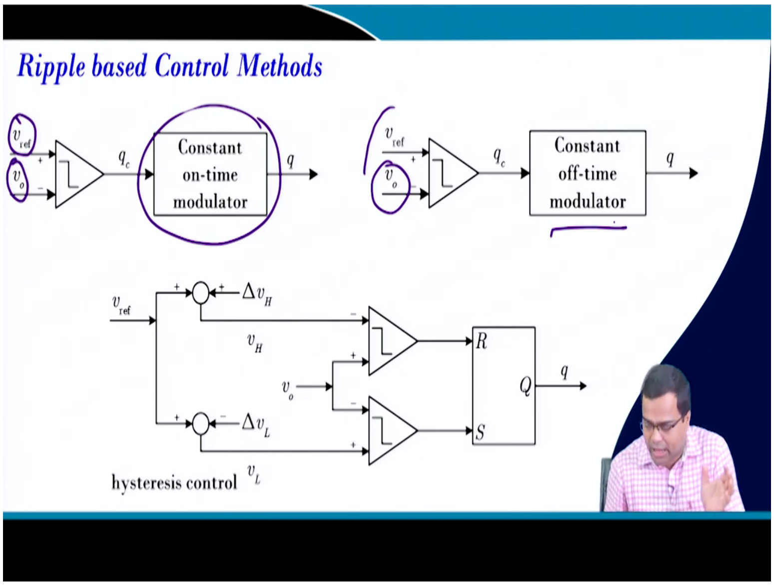
So, if we can do that then we can push the performance up to the physical limit and go beyond the conventional notion of control bandwidth.

(Refer Slide Time: 33:21)



So, the first thing I want to show ripple based control. So, constant on time control and constant off-time control and the hysteresis control. And we will detail discuss in the subsequent class all these control techniques.

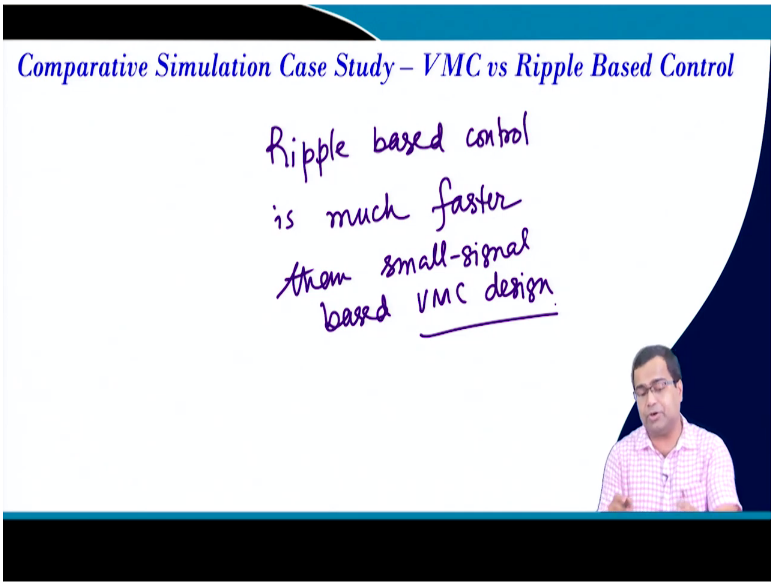
(Refer Slide Time: 33:32)



But, we want to show a ripple based; so, what are the structure? In the ripple based control the output voltage is directly compared with the reference voltage. And, the comparator output goes to the modulator constant on time modulator.

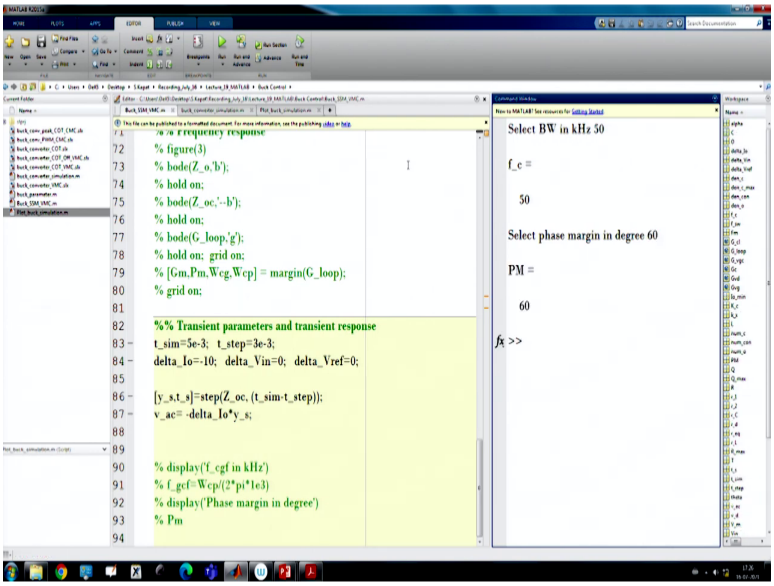
So, here there is no compensator right, so we are getting the full output voltage with ripple information. Similarly, the constant off time we can retain the output voltage ripple information and we can just change the moderator here ok. And, the third one is the hysteresis control, where we can retain the ripple information directly, because the hysteresis directly works on the ripple of the voltage or current depending upon what kind of hysteresis control you are implementing.

(Refer Slide Time: 34:15)



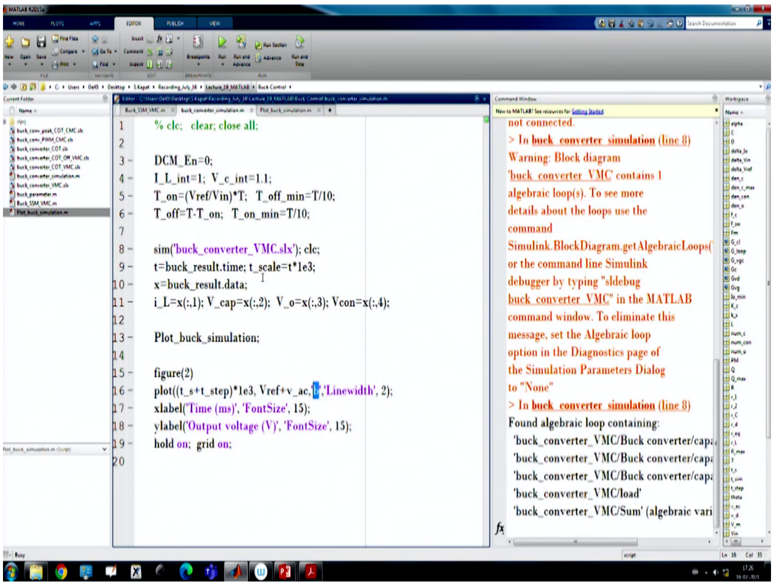
So, I want to show you one case study. The voltage mode control versus ripple based control. So, let us go back to our MATLAB case study.

(Refer Slide Time: 34:30)



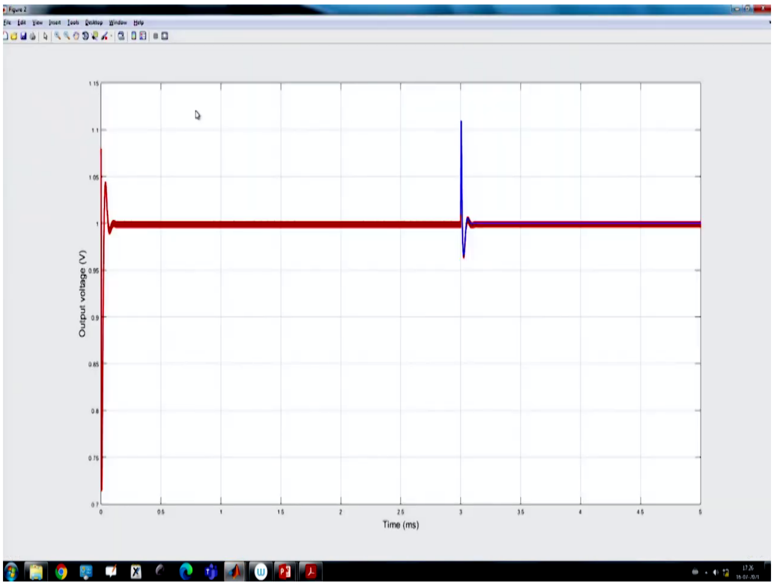
So, if you go back on top of this; that means, we are again we are going back to our 50 kilohertz bandwidth because we know the model is valid for small signal based design.

(Refer Slide Time: 34:38)



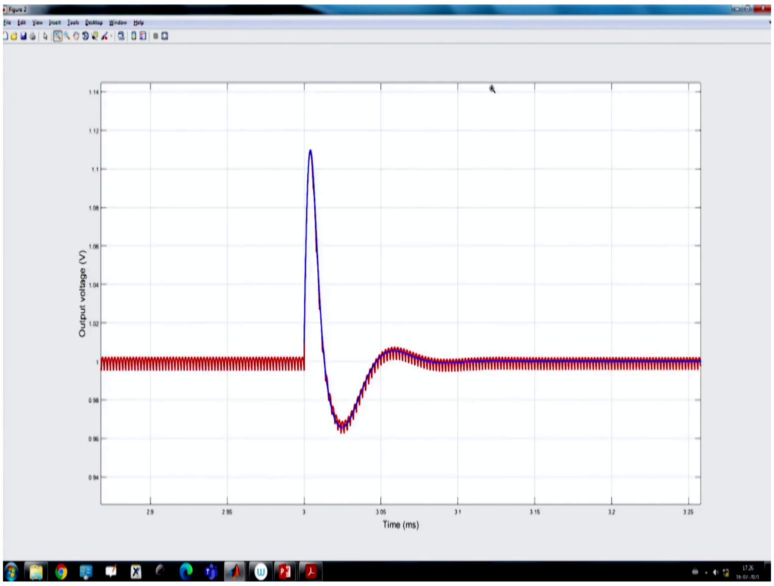
And, we want to simulate our converter response.

(Refer Slide Time: 34:41)



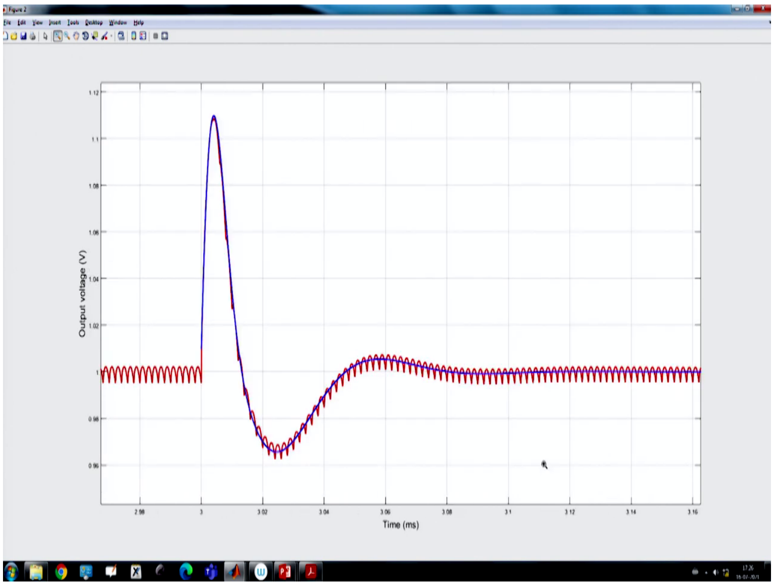
And, this response is coming you know we have some overshoot undershoot in the output voltage.

(Refer Slide Time: 34:46)



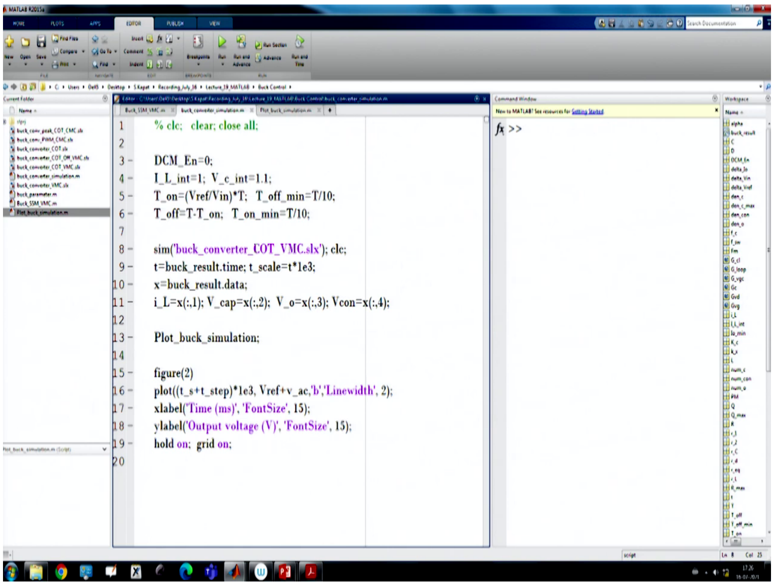
And, this is matching perfectly.

(Refer Slide Time: 34:48)



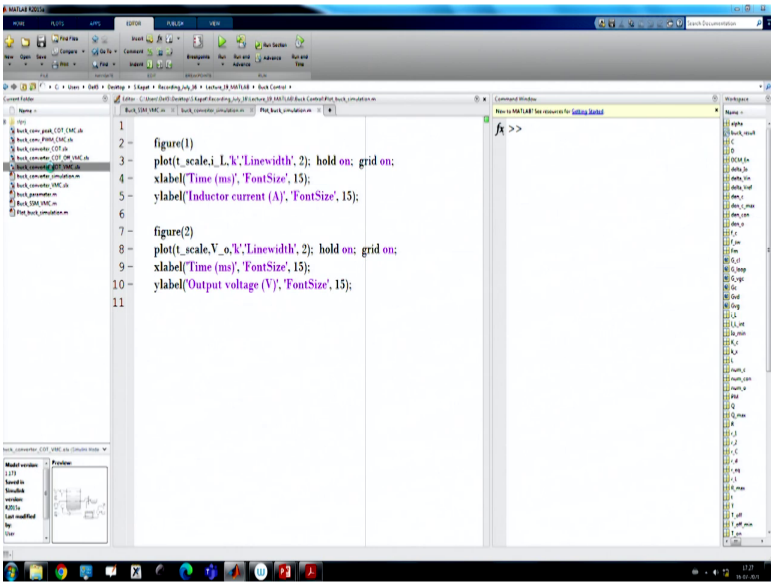
So, this is somewhat the achievable bandwidth from the closed loop control using small signal based design.

(Refer Slide Time: 34:57)



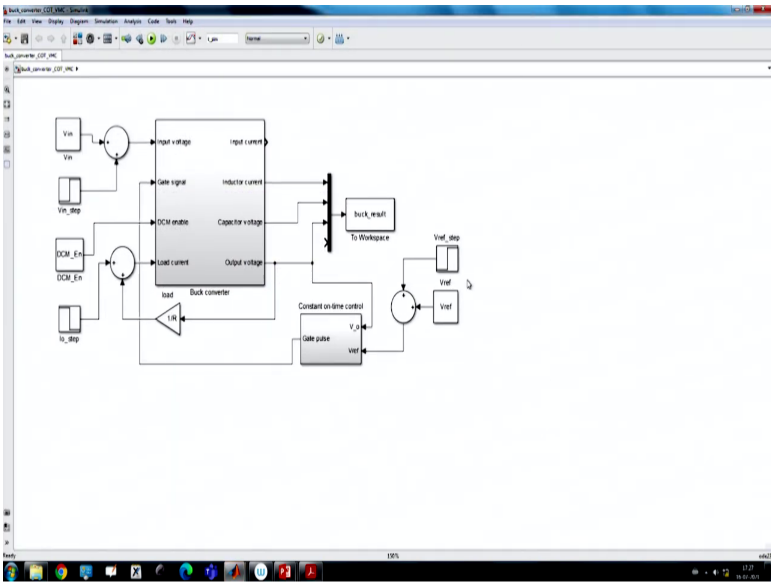
Now, suppose we want to incorporate constant on time control, because I have a you know constant on time.

(Refer Slide Time: 35:08)



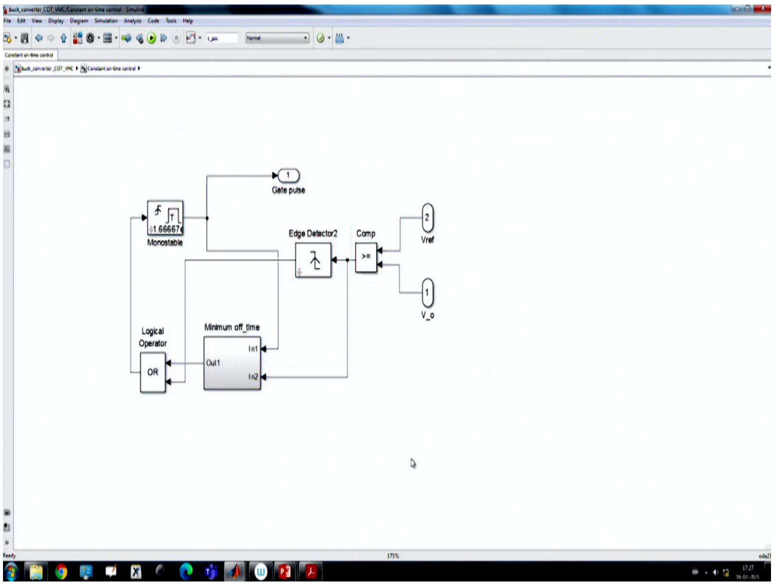
So, I want to incorporate, and I am using the black color. So, if you go to constant on time VMC. So, this is the block diagram, here because we have already shown the block diagram for voltage mode control.

(Refer Slide Time: 35:21)



In constant on time control, we are just taking the output voltage and the reference voltage.

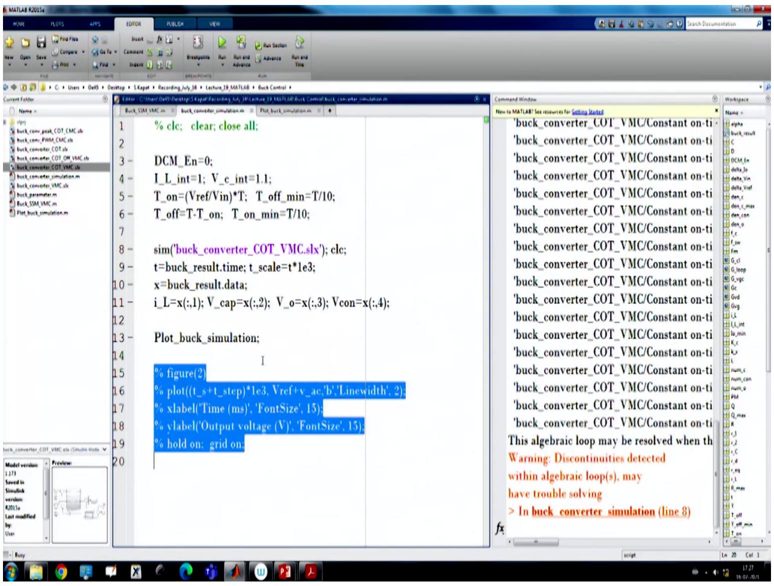
(Refer Slide Time: 35:28)



And, if you go inside, they are directly compared using a comparator. This is a comparator ok. So, this is; that means, the direct control and this is the whole block is our constant on time modulator, because we have discussed in; and in we will discuss in the subsequent lecture that you need to incorporate a minimum off time so that I it will not collapse.

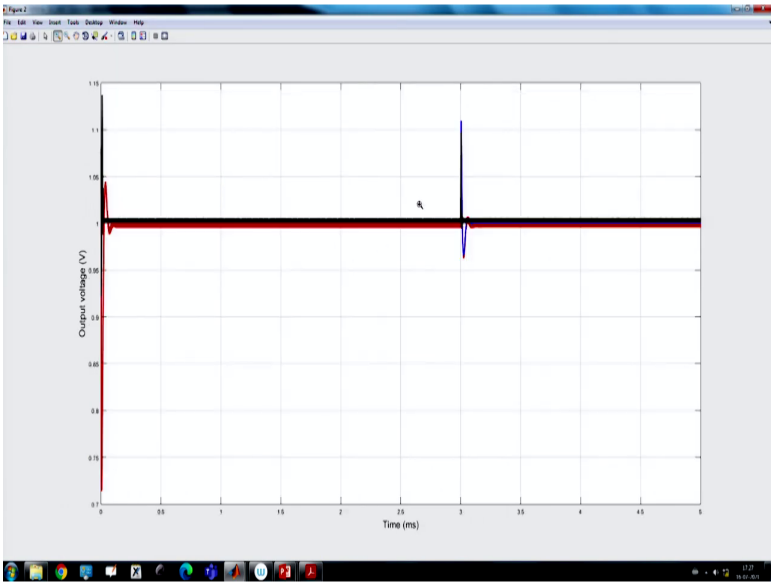
So all this part will discuss, but in this simulation we want to run this simulation and check.

(Refer Slide Time: 35:54)

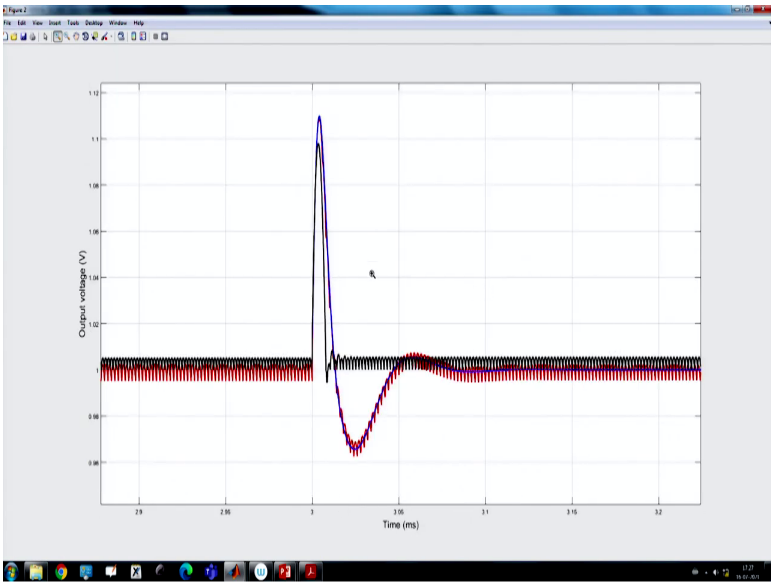


How does the response look like when you use a constant on time control, ok? So, we are using a black trace to show the response due to the constant on time. And already we have a used a voltage mode control fixed frequency.

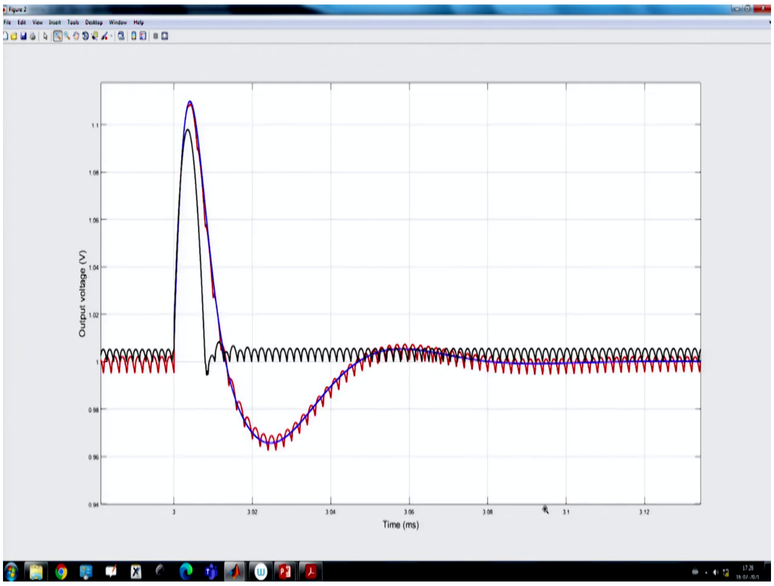
(Refer Slide Time: 36:08)



(Refer Slide Time: 36:09)

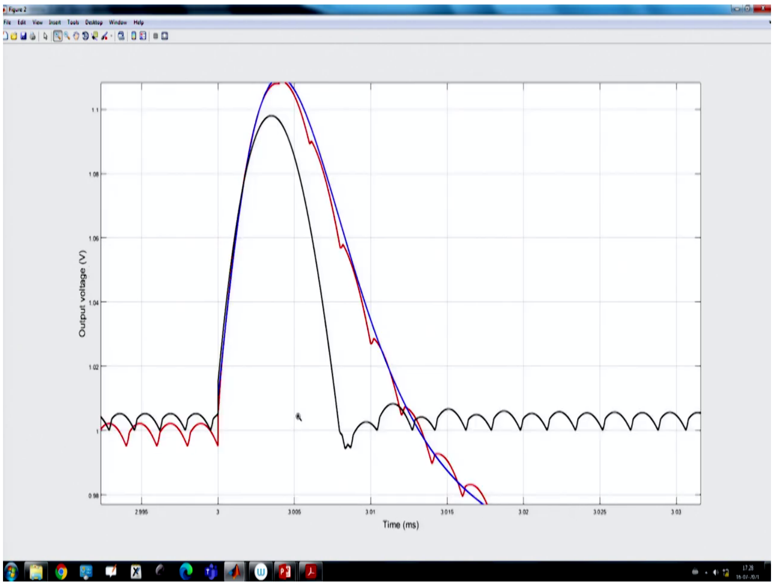


(Refer Slide Time: 36:12)



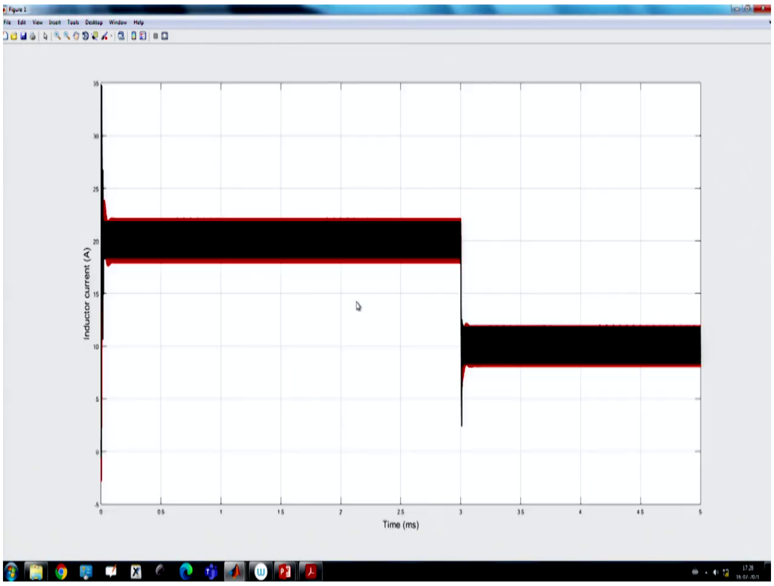
Now, if you see the response, the black color is the one which you obtained from ripple based control.

(Refer Slide Time: 36:15)



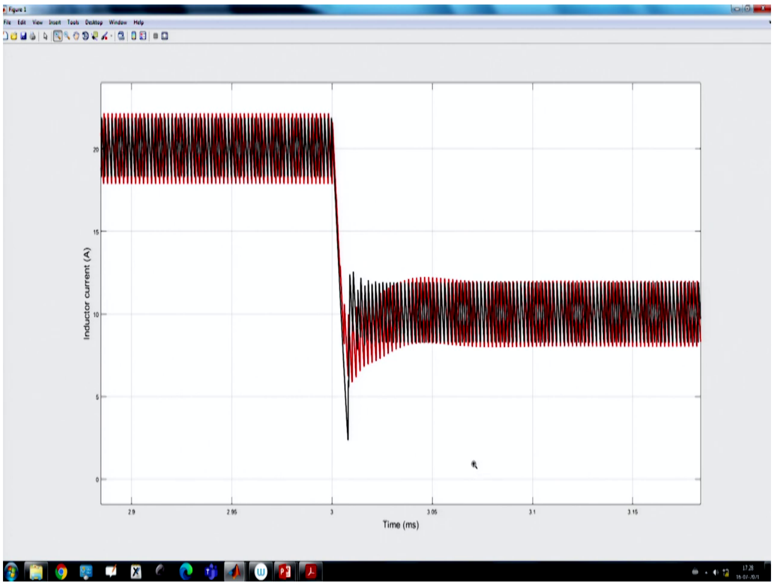
And, if you go as if it is very fast I mean extremely fast and if you go to the inductor current waveform.

(Refer Slide Time: 36:21)

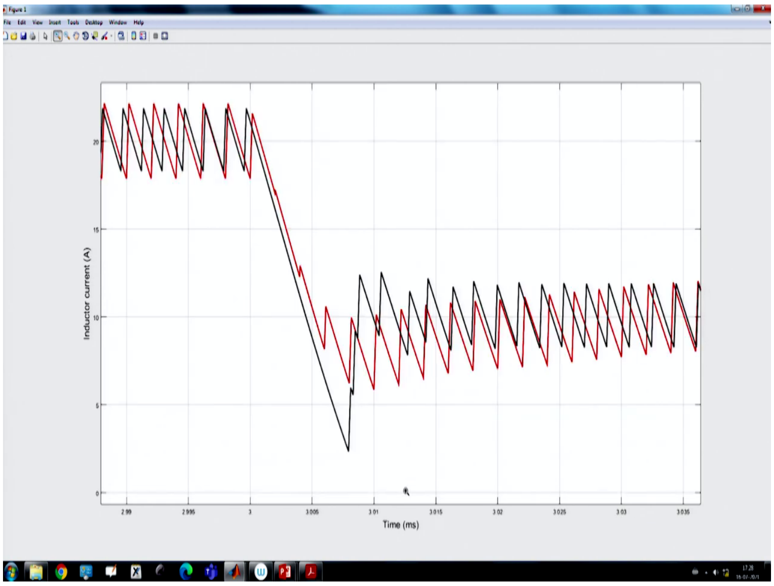


So, I want to show you that.

(Refer Slide Time: 36:26)

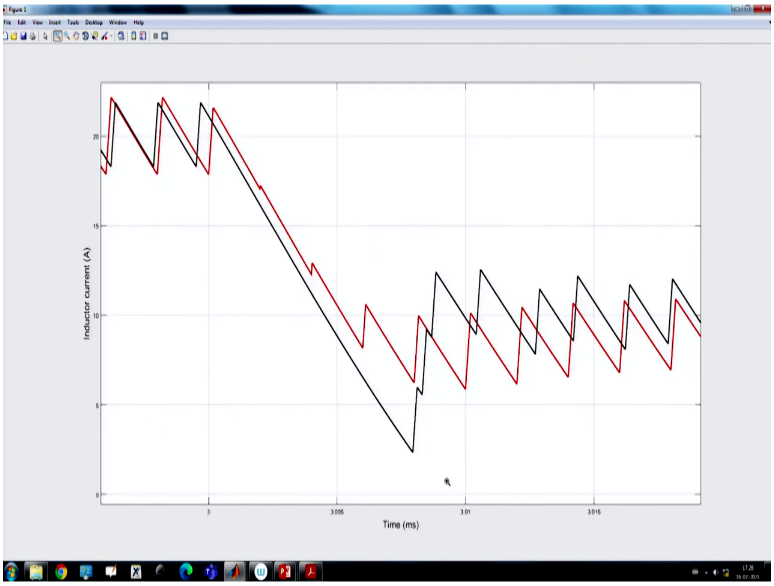


(Refer Slide Time: 36:28)



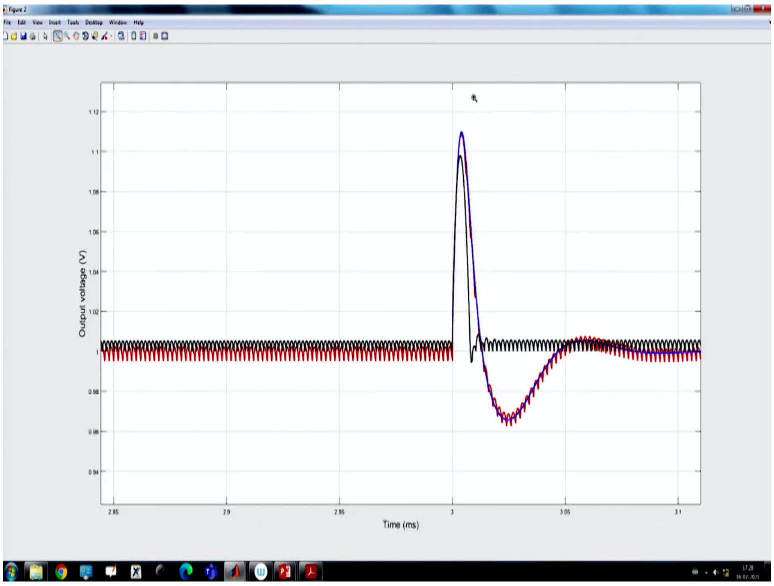
So, the red one is coming from our small-signal model like a voltage mode fixed frequency control and the black one is coming from our constant on time control.

(Refer Slide Time: 36:33)

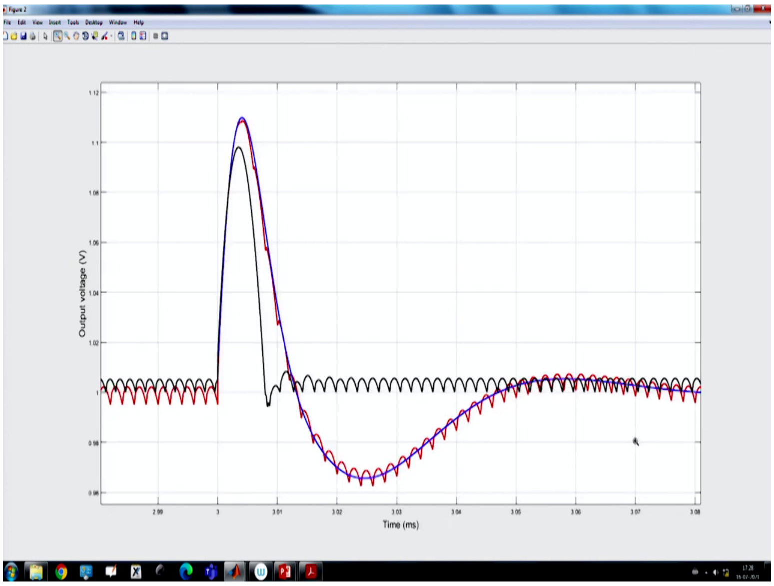


And, you can see it is responding very fast and it is reaching steady state much faster, ok.

(Refer Slide Time: 36:46)



(Refer Slide Time: 36:49)



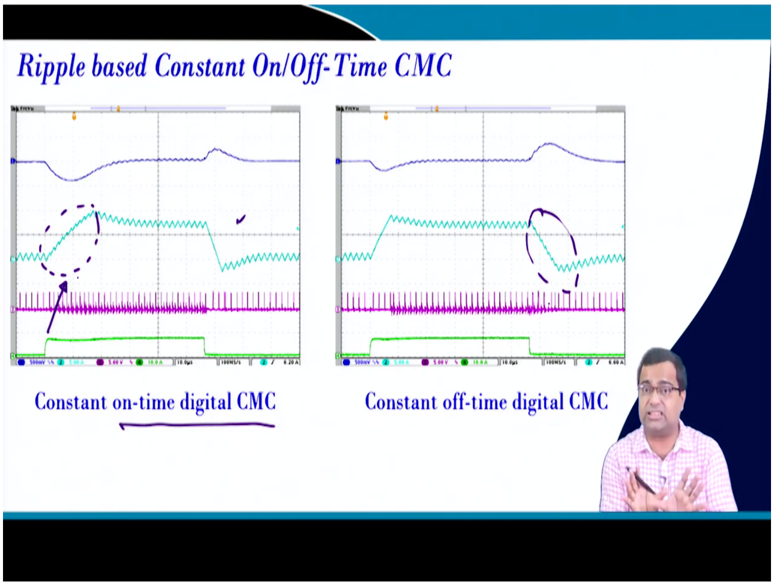
Whereas, because of the small signal based design, so, our overshoot during the step down transient is pretty much higher ok. So, the constant on time control since it directly works on the ripple based approach. So, it can be really fast response, very fast response can be achieved ok.

So, now, we are going back to our original discussion. So; that means the ripple based control is much faster; the ripple based control, ripple based control is much faster, much faster than small signal based; small signal based voltage mode control design ok.

Because, why are saying even we will see if you go for large signal based voltage mode control design, even it can be faster than that ripple based control, but we are not discussing. And that is one of the major theme of this course at the end, we will show the last single based control can improve the performance drastically, ok.

But, now we are showing just small signal based approach because of the bandwidth limit ok.

(Refer Slide Time: 38:01)

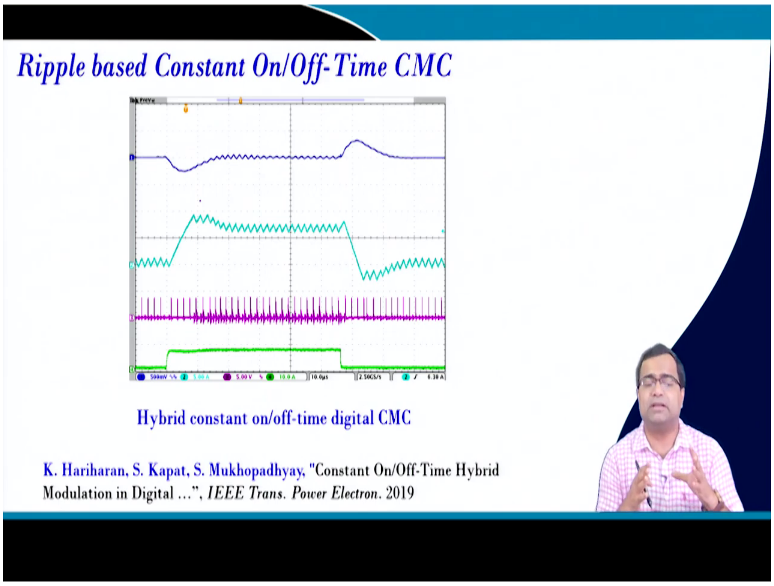


So, I will just want to show a few experimental case study. This is a the constant on time digital current mode control, where you know in the constant on time we have discussed that you need to put a minimum off time ok. That means, the constant off time on time it can be shown and it is well reported, it suffer from poor transient performance when you go for step up transient ok.

And, people actually use an adaptation of on time in order to improve that, but if you use a traditional constant on time control, your step up transient will be penalized, but the step down transient is excellent. If you go for constant off time control, then the step up performance is very nice, but the step down will be penalized because you need to incorporate a minimum on time, ok.

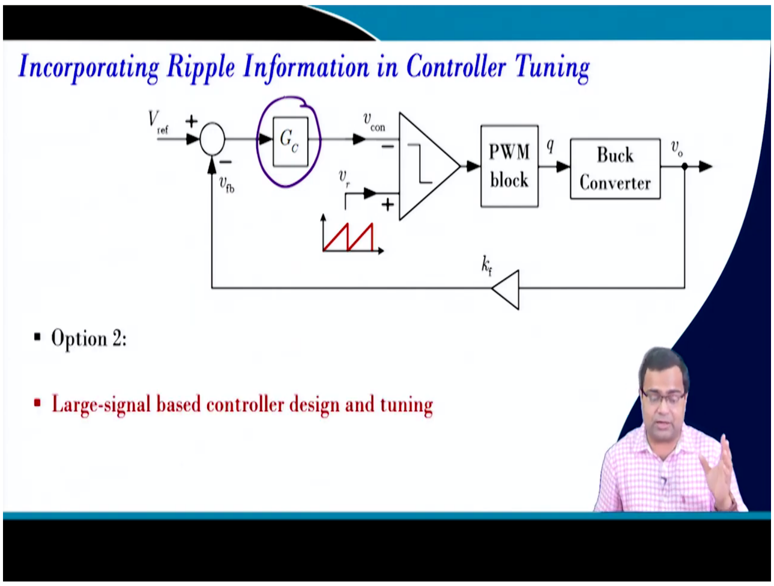
And, that we will discuss in the subsequent lecture, why do we need to put a minimum off time for constant on time control and the minimum on time for constant off time control ok; because otherwise it will collapse.

(Refer Slide Time: 39:04)



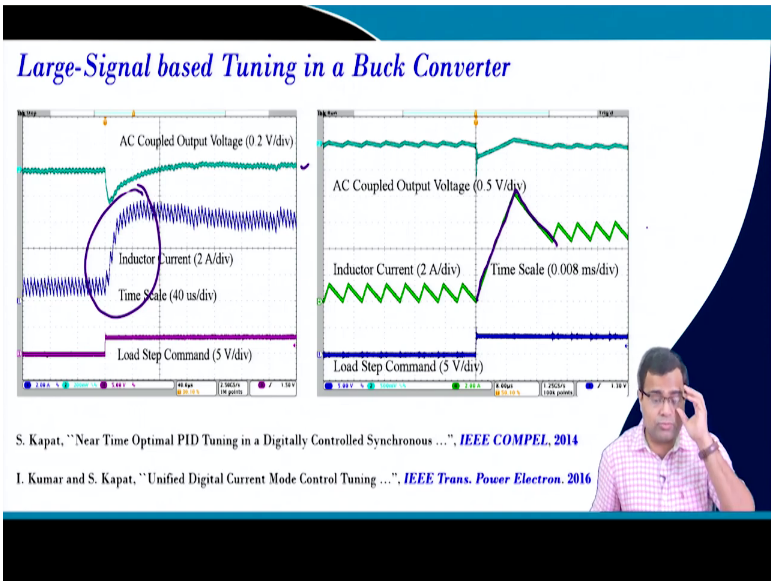
Then, the ripple based control. If you actually we have proposed that hybrid digital current mode control, where you take the best of constant on time and off time just by a simple modification of the clocked signal, without changing the hardware. So, it is achieved it is we could retain the very fast transient response.

(Refer Slide Time: 39:25)



Now, incorporating ripple information in controller tuning. As I said that you can design the controller by considering the current ripple. I mean, we are not going to restrict the small-signal model that is option 2.

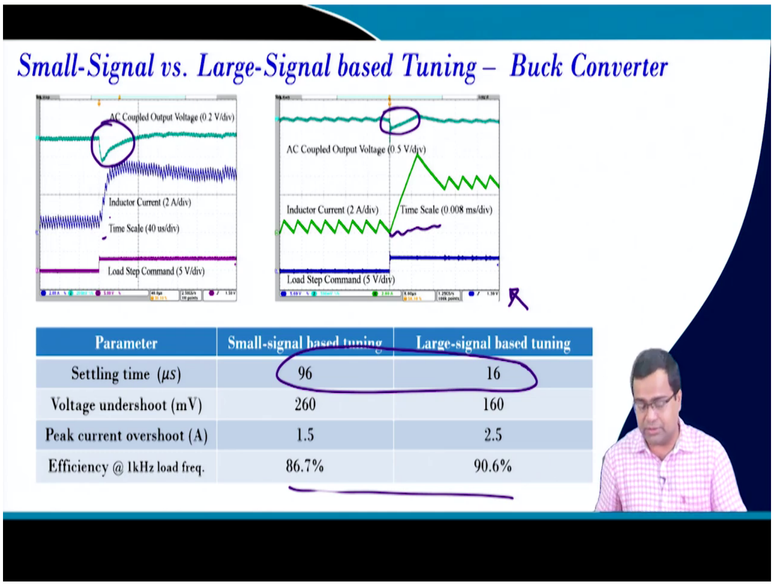
(Refer Slide Time: 39:41)



And, if you do that then you can actually this is the small signal based design. That we have discussed; using small signal based design, and this is the large signal based design. The same converter by using a large signal base approach,because, in traditional control during transient, the duty ratio variation has to be small. Otherwise, a small-signal model is not valid and that limit the performance.

But in large signal base control, you allow the duty ratio to saturate, so that it will sleeve up and sleeve down quickly come down in one switching action. And, sometime we call it as a time optimal control. It is the fastest control, and that is possible using our traditional PWM controller by using a large signal based tuning method ok.

(Refer Slide Time: 40:28)

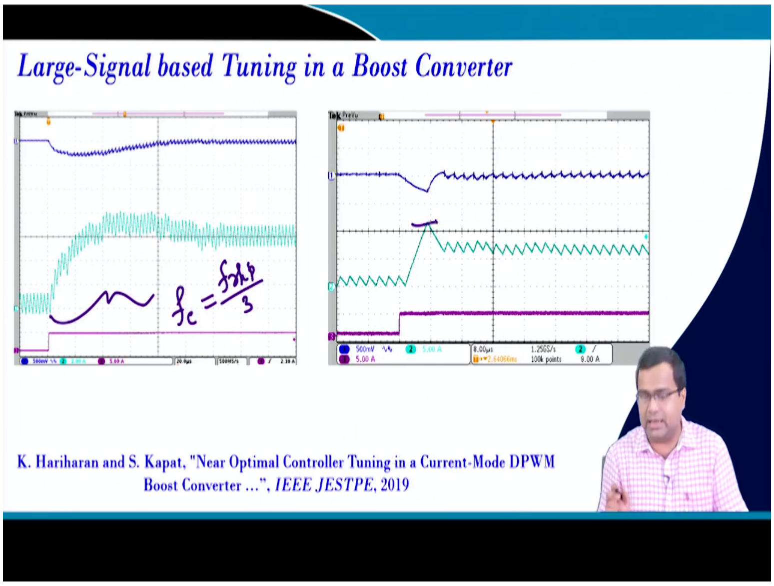


So, now we have extended; that means, this control technique can significantly improve the recovery time of this converter. So, here we are achieving almost 6 time faster response. And, you can reduce the undershoot of the output voltage; you can see it is much higher you can reduce. As a result, this also gives us you know a flexibility to reduce the further output capacitor value. So, you can in fact design you know smaller output filter or output capacitor. So, the power density can be increased.

And, it can be shown if such frequent load transient happens, this second approach can even save power or it can achieve high efficiency, because the number of switching during this recovery process is much less compared to our traditional control.

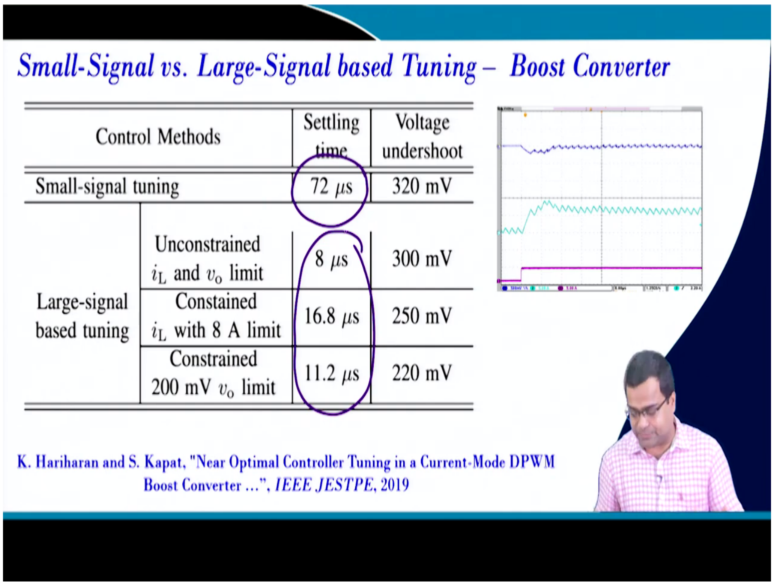
So, we will discuss this in detail in the lecture in the later part of this course.

(Refer Slide Time: 41:22)



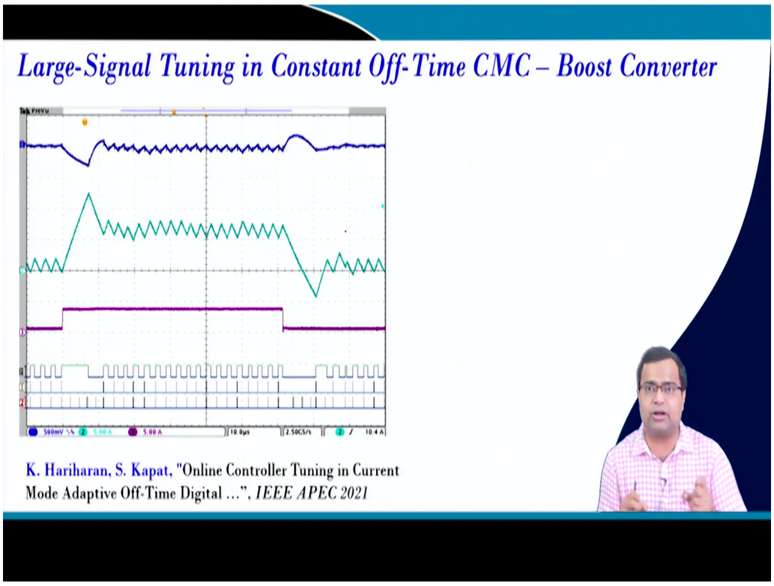
But, we can use this for boost converter and you can substantially, because the boost converter when you design voltage mode control, even current mode control; we will see the current mode control your bandwidth of this or crossover frequency will be limited to f rhp 0 by 3. And, that makes the whole boost converter control response is very slow. But if you go for large signal based control, you can increase even 8 to 10 time faster.

(Refer Slide Time: 41:50)



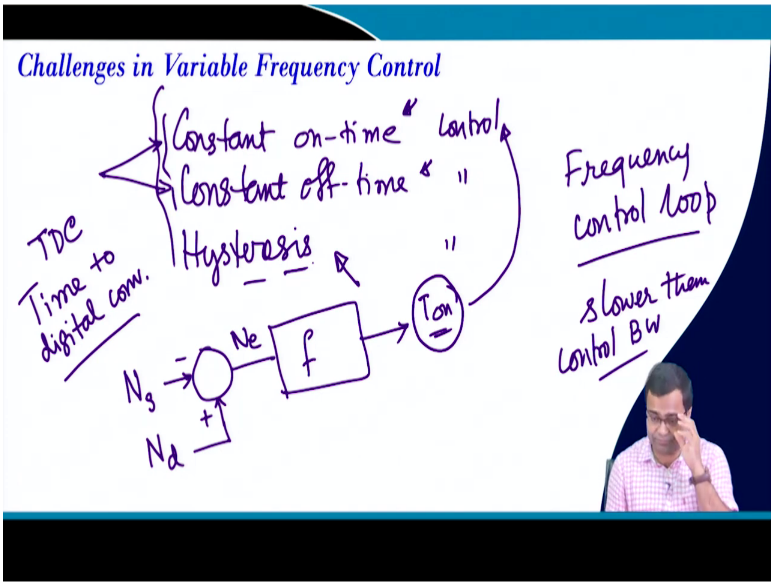
So, that boost converter we can. And, but the earlier was the current ripple; current peak current was high so you can put a current limit and you still can achieve. So, a small signal design it takes 72 microsecond, for 2 microsecond time period whereas, all other approaches that we have developed it can really speed up the response.

(Refer Slide Time: 42:11)



So, the bottom line is these that large signal based tuning can be incorporated to improve the transient performance.

(Refer Slide Time: 42:19)



So, the challenges, but what are the challenges in variable frequency? So, one we talked about constant on time control right; we talked about constant on time; we talked about constant off time and we talk about hysteresis. And we will take detailed comparison. You know all these are control, control, control and control.

So, all these suffer from variable frequency operation. Then, how can we regulate the switching frequency? That is why many of this technique is not used for you know nominal load condition, but now you can incorporate another loop, which is the frequency control loop, the frequency control loop; another loop feedback loop. This loop is used to adjust the on time for this case or off time for this case or the hysteresis band for this case such that your overall time period will reach closed to the desired value.

So, that means, but this frequency loop is much slower than much slower than control bandwidth. Otherwise, they will interfere interact, so it is much slower than the control bandwidth. So, the variation of the on time or off time or adaptation happen very very slowly, but if you can implement, then you can achieve nearly regulated you can regulate the switching frequency. And, for these two techniques, it is somewhat straightforward, because if you take the time to digital converter, time to digital converter; that means, time to digital converter.

So, you can get the instantaneous time period and you can create a feedback loop and compare with the desired value. So, let us say this is your actually on time on time which are instantaneous, and this is your desired. So, what you will do; this will be subtracted from your desired value, because these are all numbers and then the error. Then you create a map a function and that will generate.

In case of constant on time, it will generate the on time adaptation. That means, just slowly adjust on time, in order to achieve the fixed switching frequency. It can also used, it can be used to adjust the off time or it can be used to adjust you know this particular hysteresis band.

So, first two technique is easy because your timer using a digital means, does it digitally assisted; that means, a timer can be a just a counter. So, you can just you know you can use a monoshot timer using digital not any analog ok. Then you can just load this counter by using this adaptive value by adaptation right and you can regulate the switching frequency.

But, the hysteresis control that we have to take seriously if it is analog, it is not very easy because it is analog you have to implement and you have to voltage control that particular band. So, you need to take special care.

(Refer Slide Time: 45:34)

So, in summary, variable control techniques are very helpful ok, but it also comes with a price that variable frequency operation. So, you need to incorporate a frequency loop, but now with the more growing towards digital control, actually these variable control, you can because in digital already have a digital platform. So, the frequency regulation loop can be simply that using all digital PLL, simply a counter based approach can be used. And, that will not take much of the resources. And, that is how you can even adjust the switching frequency very effectively.

So, the ripple based control motivating case study we have demonstrated. And, now this also tells us that the current commercial products are coming up with more ripple based control ok. Because, particularly for low duty ratio operation if you go to multi phase converter, you know most of the manufacturer or the vendors in current mode control; they are coming with constant on time control. The MATLAB case studies we have demonstrated and we have also demonstrated few experimental case studies.

So, with this I want to finish it here.

Thank you very much.