Control and Tuning Methods in Switched Mode Power Converters
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Module - 07
Small-signal Design and Tuning of PWM Voltage Mode Control
Lecture - 33
Loop Gain Analysis and Understanding Model Limits Using MATLAB

Welcome, this is lecture number 33. In this lecture, we are going to talk about Loop Gain Analysis and Understanding Model Limit using MATLAB.

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So, in this talk, we are going to first you know construct the small-signal closed loop block diagram, then we need to understand the loop gain and its design requirement, then we need to validate closed loop small-signal model using MATLAB transient simulation and here I am taking a PID controller case study and try to identify the model limits ok.

So, with this, you know today's presentation, mainly in the previous, I think lecture number 30 we have talked we have shown the detailed process how to validate small-signal model and that was for open loop converter. So, we want to take that as the reference class for this today class so that we can you know some of the step we can just skip because that was discussed in lecture number 30.

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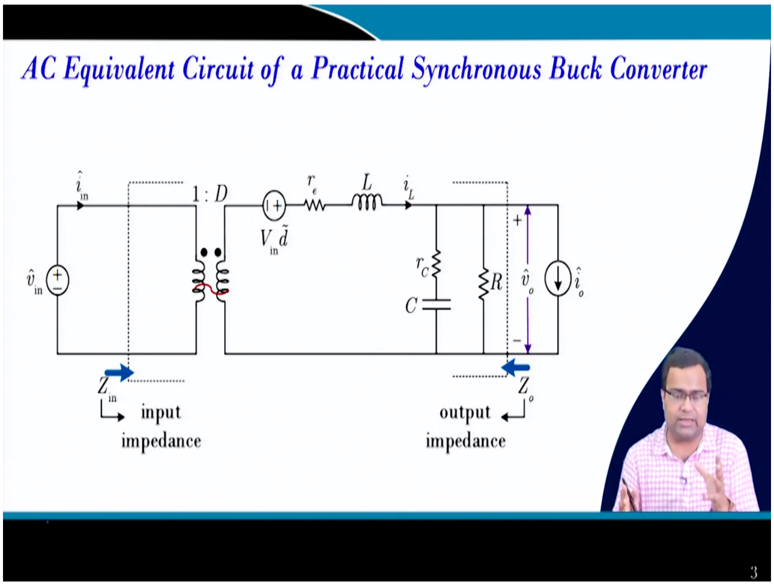

So, in AC equivalent circuit of a practical synchronous buck converter that can be you know we have already obtained in the previous lecture. And we can obtain any output impedance, input impedance, audio susceptibility, control to output transfer function.

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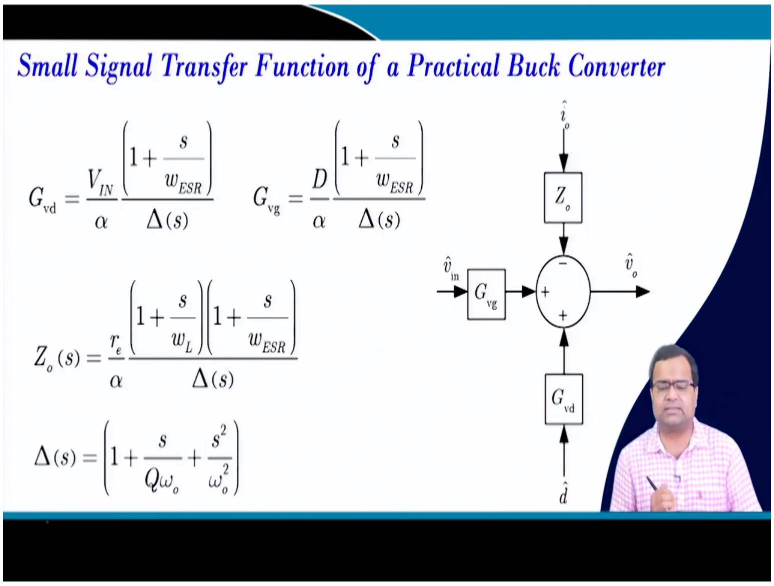

And these are the summary of transfer function of a practical buck converter. This is a control to output transfer function. This is one of the most important that we are going to deal with. Audio susceptibility is also very important; then output impedance is very important and for all these transfer functions, the common denominator which is the pole is nothing but this transfer function ok. And this is a small-signal block diagram for the open loop converter alright.

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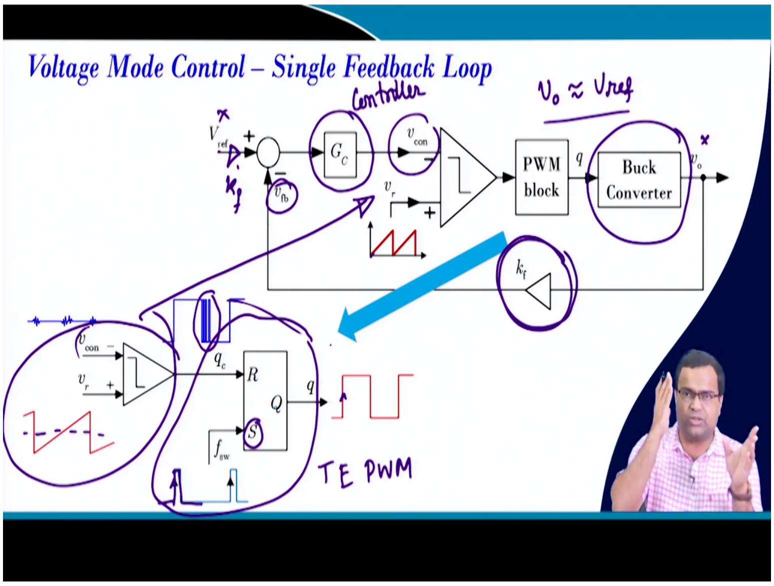

Now, we want to first go for voltage mode control. Today's discussion, we want to talk about single loop control and in subsequent lecture, we will go for two loop control in current mode. But in single loop control, we want to restrict our discussion of loop gain analysis for single loop voltage mode control.

So, you know that if we take any DC-DC converter, here it is a buck; but it can take a boost converter, you can take fly back converter, you can take buck-boost converter. If you take the output voltage, then this is a feedback voltage and generally, this feedback gain comes from the resistive divider and that we have discussed.

Then, it is compared to the reference voltage. In fact, reference voltage also there should be a gain, feedback gain because you need to scale the reference voltage accordingly in order to match; that means, our objective ultimately to obtain v 0 equal to v ref as steady state desired voltage. So, if you step down by a factor of K f.

Then, you have to make a scaling factor here. So, that v ref to v 0 can be mapped. Next, what is PWM modulator? Here, we have a sawtooth waveform and the control voltage, which is the output of the controller. This is our controller right. Sometime, it is also called compensator controller. So, now, this PWM block actually this block is already there; so, this block is here, here.

So, this PWM block is this which is a trailing edge modulation. This is our trailing edge PWM block. Why? Because the switch turns on at every rising edge of the clock switching clock, it set the pulse. So, switch turns on; switch turns on. And switch turns off, when the control voltage intersects with the sawtooth waveform; that means, when it intersects, ok.

Now, and it has a latch circuit to avoid this jittering you know behaviour, comparator behaviour, it should not be reflected in the output side. So, latch will make sure that once the switch turns off, it will not be turned on throughout the rest of the interval.

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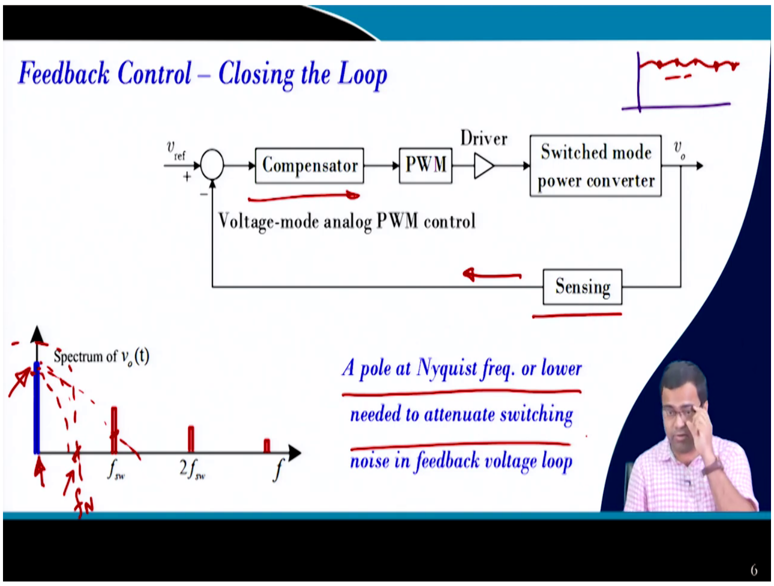

So, now we are closing the feedback loop. We saw the output voltage as if we draw the output voltage waveform; it has some amount of switching frequency ripple. In fact, in practical converter there should be some you know due to ESL effect, you know for boost converter anyway this direct jump will be there due to the ESR.

So, when you sense the voltage and if we use a high frequency, I would say high frequency op-amp right. So, this switching ripple information will be passed to this loop; that means the loop will say the switching frequency ripple information. But we will discuss today that our small-signal is valid within a certain restricted bandwidth limit.

That means, whatever you talked about, the control bandwidth of a DC-DC converter using small-signal based design, it is coming due to the model limit ok. So, wherever our actual transient response using small-signal model as is as long as it is matching with the switch simulation under closed loop, up to that point we can go for you know we can increase the bandwidth.

Beyond that, the model will start, there will be mismatch, and our model is not valid. So, that means, we need to slow down this process because of small-signal model and, but before start discussing, we cannot introduce the switching harmonics or switching ripple into the loop.

And if you take the power spectrum of the output voltage, in fact, this should be even smaller. So, it will have a very high component of the power, which corresponds to the DC component because it is ultimately DC-DC converter ok. But there will be some component in the switching frequency and harmonics.

So, in order to avoid that means, we want to attenuate that the switching frequency component should not be injected into this compensator or the PWM. So, we need to put a low-pass filter here; that means, typically, this is called we called as a Nyquist frequency; f Nyquist because it is generally half of the switching frequency and our small-signal model is not valid.

In fact, our averaging technique is not valid beyond f S by 2 which is the half of the switching frequency and our small-signal model even is not valid. We will show is more than one-tenth of the switching frequency ok. So, we are talking about Nyquist frequency, where our validity of the average model will come.

The average model concept is not applicable beyond that. But we need to put a low pass filter to attenuate because low-pass filter, it cannot immediately. So, it should attenuate this effect ok. So, that means, in order to attenuate, we need a pole either at Nyquist frequency or the lower frequency that is needed and we will see that we will have pole there.

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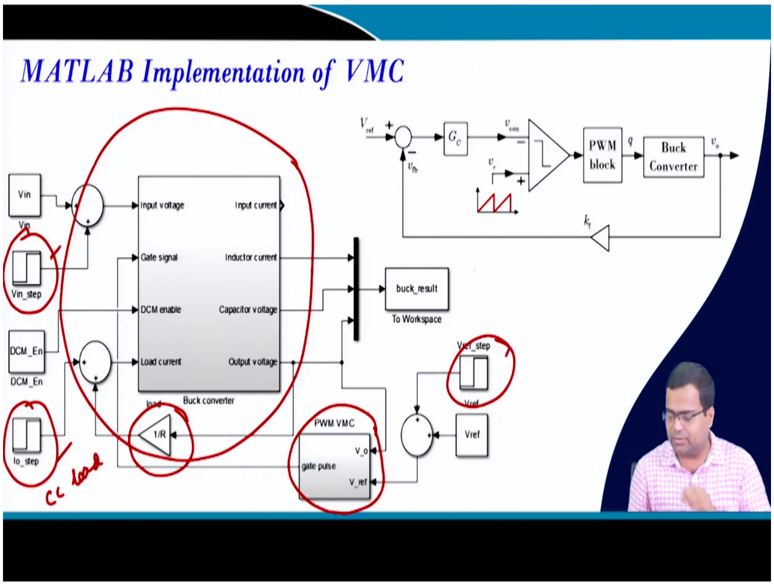

So, now the MATLAB implementation of voltage mode control, I think that we have discussed. So, this block, we have already simulated. This is our buck converter, resistive load and we are considering additional transient you know load step transient, supply transient, load transient, then reference transient; here using a constant current load, constant current load ok, load transient and this is the block diagram.

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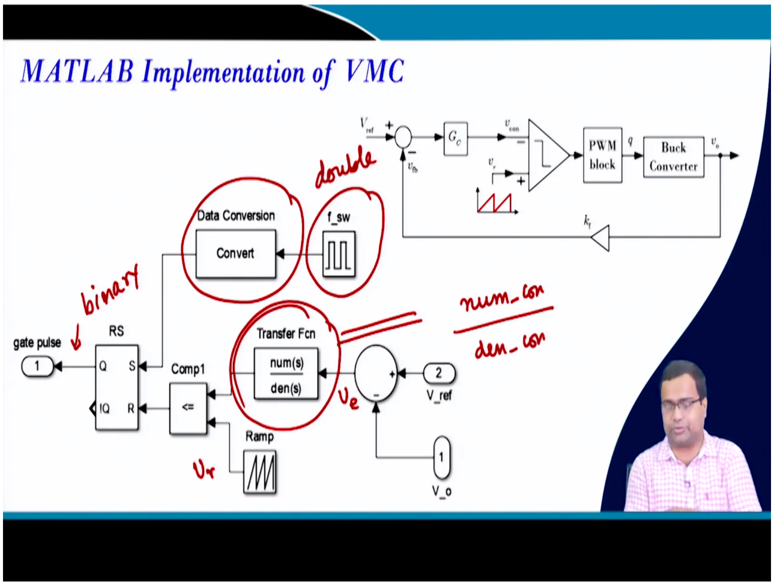

And if you go inside this block; that means, if we go inside, this is our controller, then we will see that here is my transfer function, here is my this is my error voltage ok and this is my sawtooth waveform, this is my ramp signal. And this data conversion block is used to you know you know avoid any incompatible data matching.

So, that is why this conversion block is used to make this switching clock, because sometimes the signal can be doubled; double format and here, it can be binary. So, in order to match such kind of binary double format, we can use simply a data conversion block. It will make sure they will be compatible.

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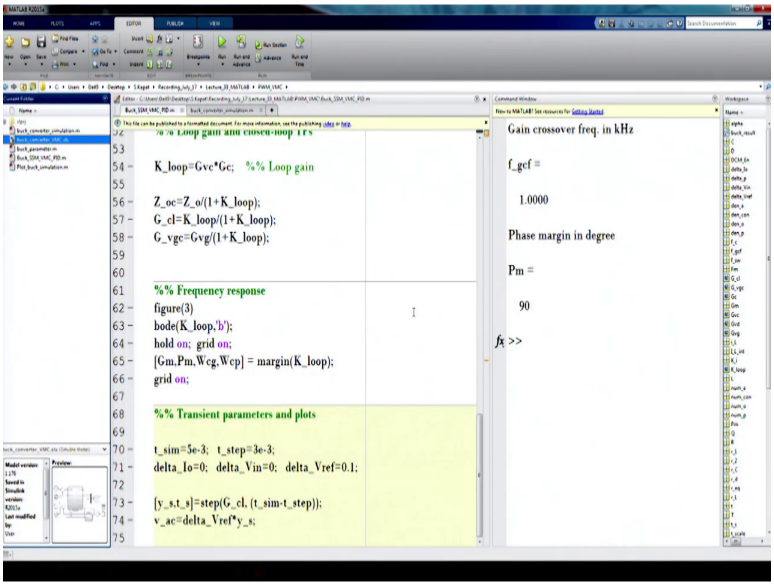

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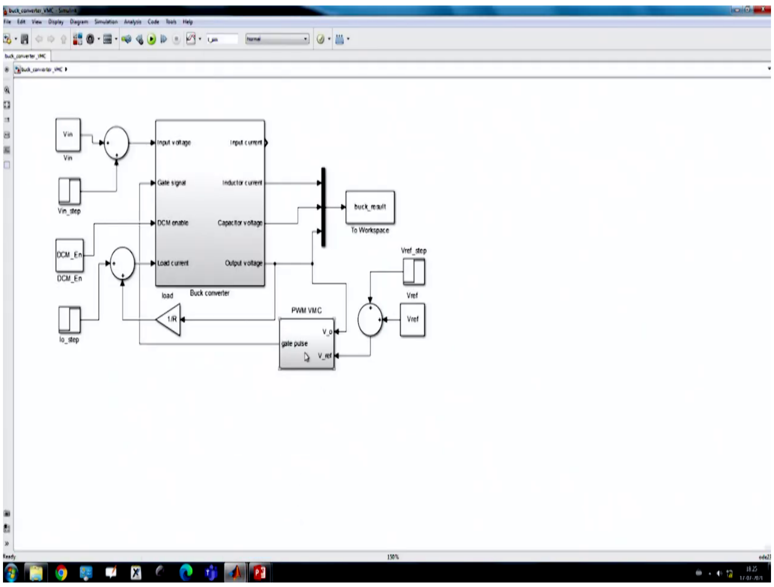

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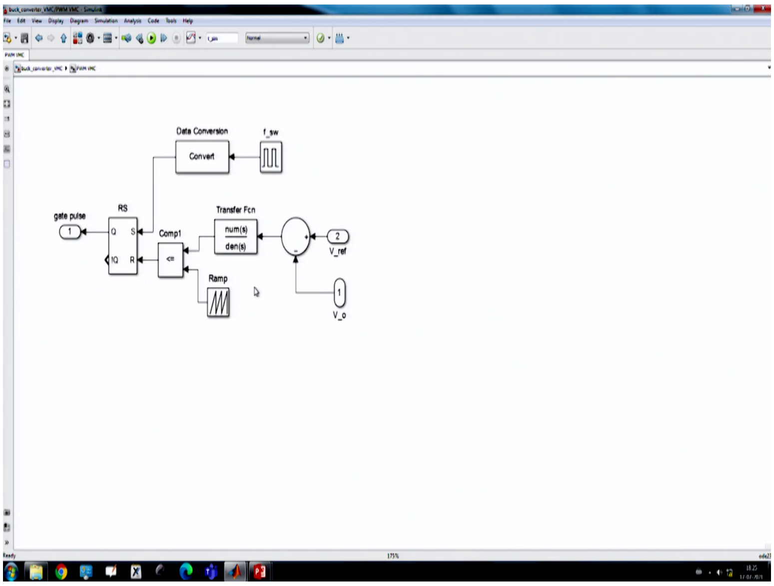

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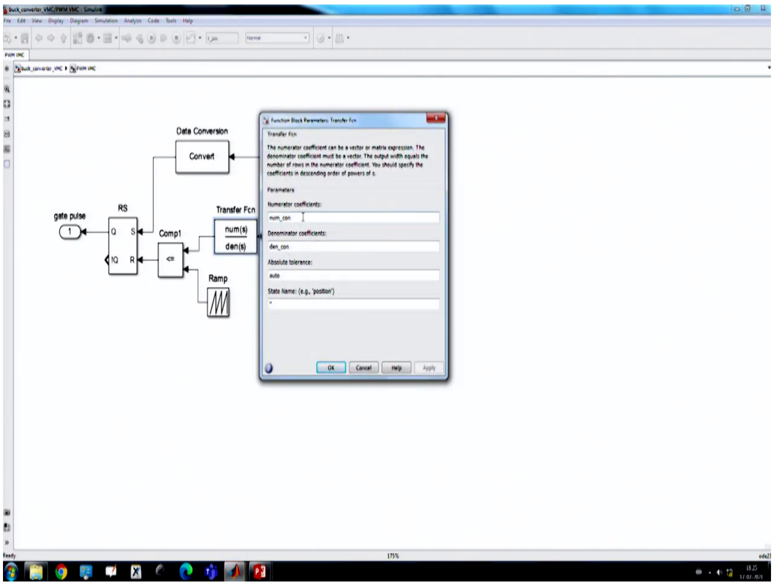

Now, this transfer function here actually if you go let us go to the MATLAB, I will show you that if you go to the MATLAB model, if you go inside, this transfer function is the one which you are calling from the MATLAB function; numerator control, denominator control ok.

So, it is that means this transfer function has numerator polynomial and divided by like a denominator polynomial. So, this will be used in the MATLAB numerator, denominator coefficient and we will this coefficient be decided from the design process.

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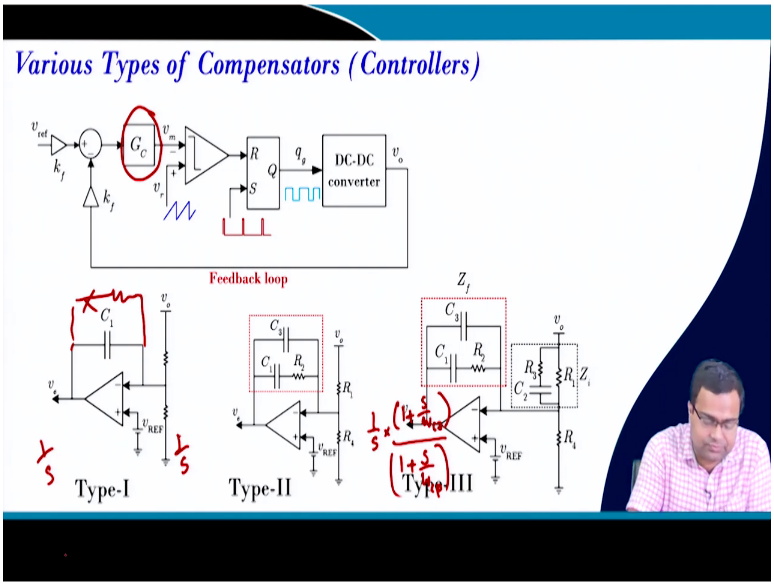

How many types of such compensators? That means we are talking about this controller. What are the; typical controller that we consider? One is type-I which is a pure integrator. Though we should not use pure integrator, we can place a pole very close to the imaginary axis. We can consider a simple resistance here to avoid sometime saturation problem of the op-amp in a practical op-amp ok.

So, type-I compensator means it is an ideal one which is 1 by S, where this resistance will not be there like a mathematically. Type-2 compensator, where we are talking about. So, here it is like a 1 pole at origin; here, we are talking about 1 pole at origin plus there is 1 controller zero divided by 1 controller pole. This is type-II and the next one is the type-III ok.

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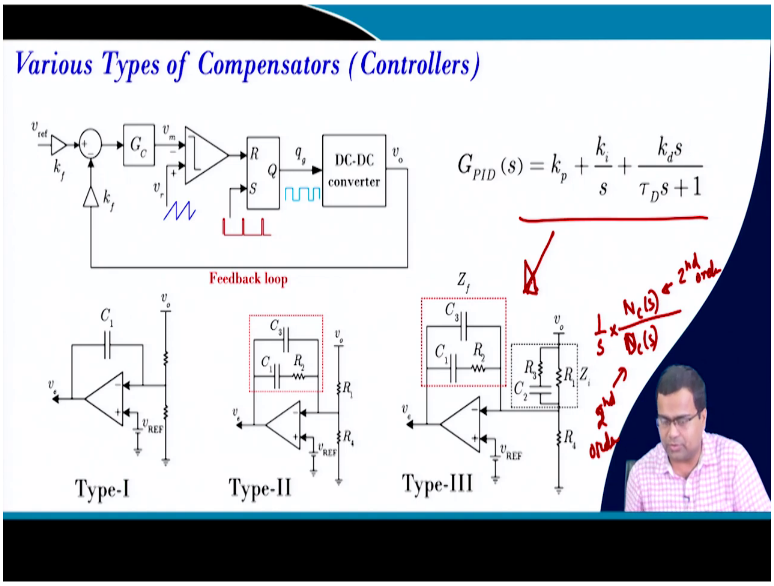

So, type-III; in type-III, we have 1 pole at origin which is common and we have 2 zero. So, that means, it is the numerator coefficient which is a second order and the denominator coefficient which is also second order sorry second order ok; second order and another is a PID controller.

So, in this particular lecture, we are talking about PID controller; but we will eventually find the PID controllers are not sufficient because of the degree of freedom, less degree of freedom when you talk about shaping the closed-loop bandwidth as well as phase margin ok.

Then, we will consider an additional pole; that means, eventually, we will go to type-III compensator in the subsequent lecture. But in today's lecture, we will talk about PID controller in order to match the model and validate the process of validation. Then, the same approach you can use for the type-III compensator to carry out the design under voltage mode control ok.

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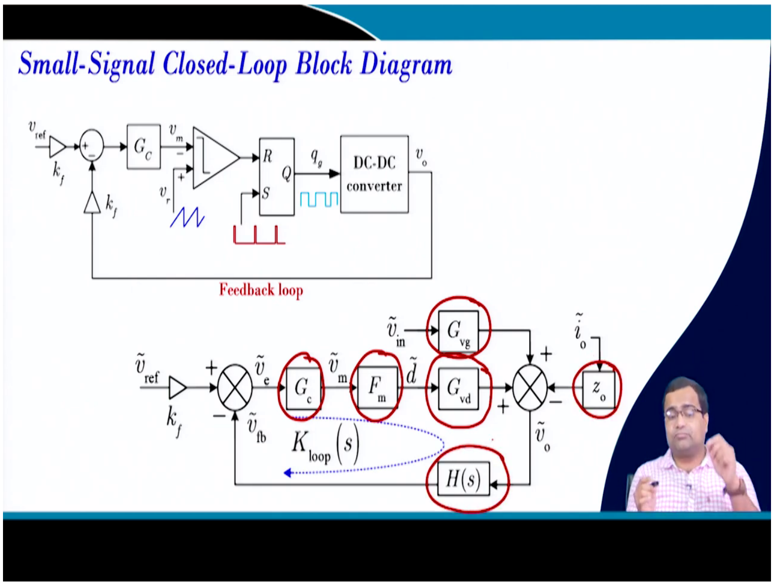

And also, it will show that PID controller is of course not sufficient for a boost converter because there is right half plane zero. So, you need to anticipate that effect using a type-III compensator, ok. So, generally, that is why the type-III compensator is a very popular choice under voltage mode control.

So, the small-signal closed loop block diagram, if you draw this feedback block diagram. So, this G vd, we have already discussed, the control to output transfer function, modulator gain, then the controller transfer function, then this is the audio susceptibility, output impedance, this is our feedback; that means, sensor.

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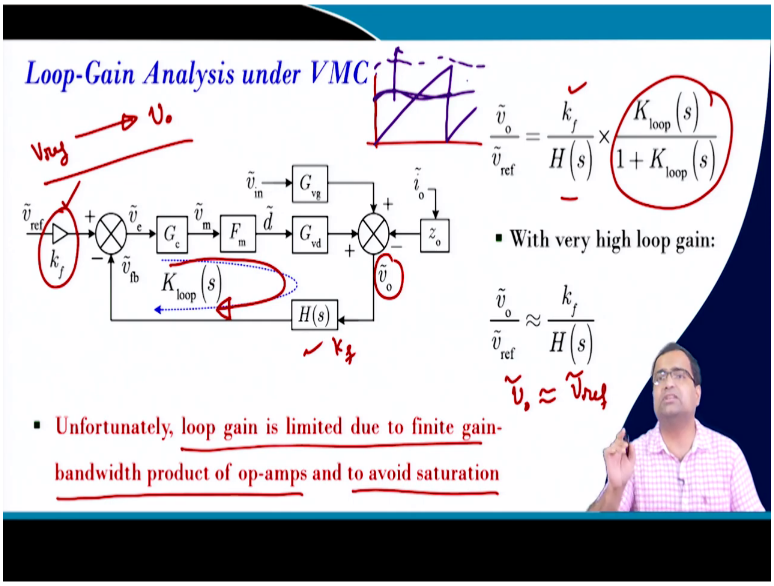

And if you want to draw the loop gain analysis, that this is our loop; this is our single loop control loop transfer function and you will find as I said that we need to map this v ref, we need to map to v 0; that means we want to make them equal. So, if we set a gain K f here. Then, this H of s should be ok first thing before we move forward mapping. So, what is our closed loop transfer function?

Our v 0 to v ref; that means, this v 0 to v ref can be written as K f, this K f H of s here multiplied by loop transfer function by 1 plus loop transfer function and if the loop transfer function is very very high, then it can be approximated by simply K f by H s. That means, if you set this also equal to K f, then your v 0 will be approximately equal to v ref. If the loop gain is very high; very high loop gain.

But this very very high loop gain requires two thing; the bandwidth of the entire range, it will be very high bandwidth and also, if the very high gain; so that means, it is not possible because our op-amp loop gain is limited due to the finite gain-bandwidth product of the op-amp and also to avoid saturation.

Because if we increase the loop gain, it may so happen their control voltage, because ultimately, what happens? There is a PWM block, modulator block. What does it do? There is a sawtooth waveform right. So, if you know sawtooth waveform, so if you take the sawtooth waveform, the sawtooth waveform. Now, this is our control voltage right. Now, if that modulator gain is very high under transient, this waveform can go above.

So, it can be like this and then, the duty ratio can saturate and under this condition, first of all, your small-signal model is not valid. Even for a large perturbation, it is not valid. The secondly, you see high DC gain, it will saturate the op-amp and we need to avoid because that analysis with saturation will go into non-linear analysis and we want to avoid and we want to restrict the whole loop analysis in terms of linear transfer function.

So, that we want to limit within the saturation limit of the op-amp. So, that means, we cannot have very high loop gain.

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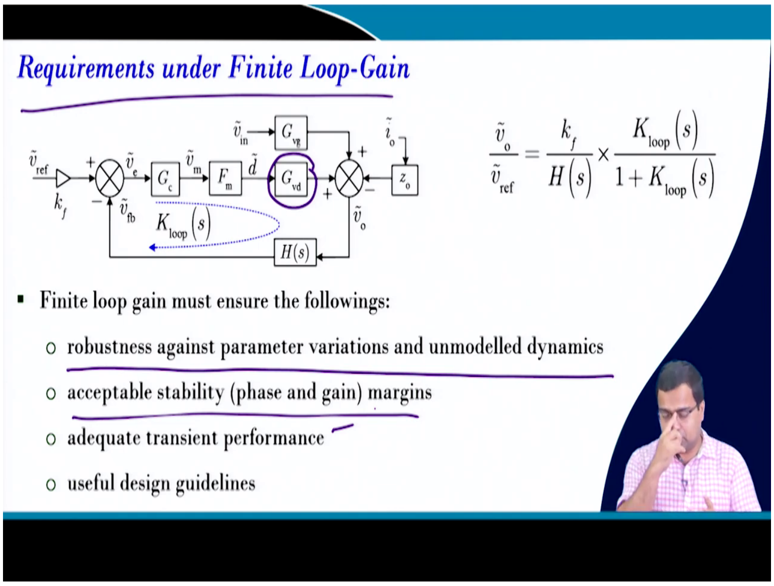

Now, requirement under finite loop gain that we have understood. So, if the loop can be finite, now what we are what we need to ensure? The robustness against parameter variation and un-modelled dynamics because the transfer function G vd here will consist of load resistance input voltage. It is also that those are the operating conditions.

Then, inductor value, capacitor value, there can be variation tolerance of the components and there are some unmodelled dynamics because we have not incorporated the dynamics of the actual switch, the dynamics of the ESL. So, there will be some un-modelled; although they are very high frequency, but that also can be incorporated.

Then, we should have acceptable stability margin, gain margin, phase margin, and we need to achieve desired adequate transient performance because we should not have very high overshoot undershoot. But our settling time should also be very fast and we should also provide some useful design guideline. So, in the subsequent lecture, we will give you all the guidelines, design guideline ok.

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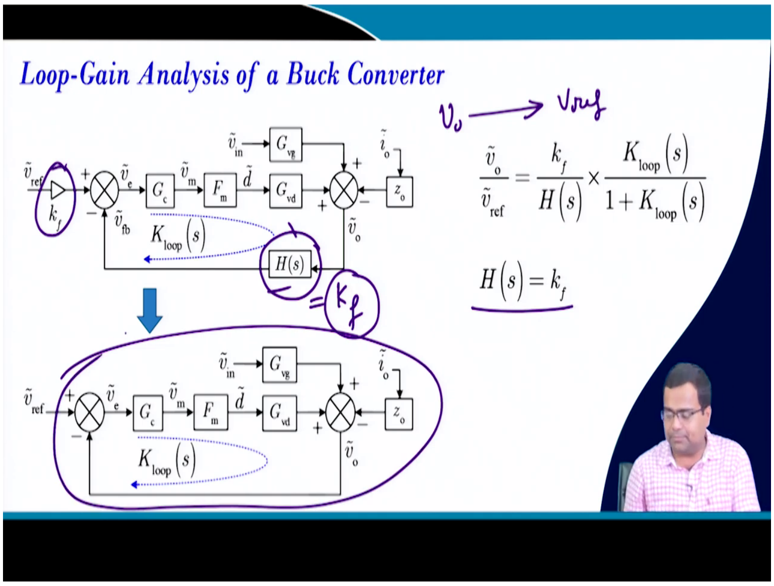

So, the loop gain analysis of a buck converter as I said that we need to map between v 0 to v ref right. So, if you set a K f gain here, then we should set the gain of the registry divided to K f and the frequency. If we put a unity gain buffer, the bandwidth of the op-amp is very high.

So, you can ignore that you know transfer function. So, the loop transfer function will loop; that means, since there is this will be replaced by K f. So, we have a K f here; we have a K f here. So, we can remove this and this will be a loop transfer function, ok.

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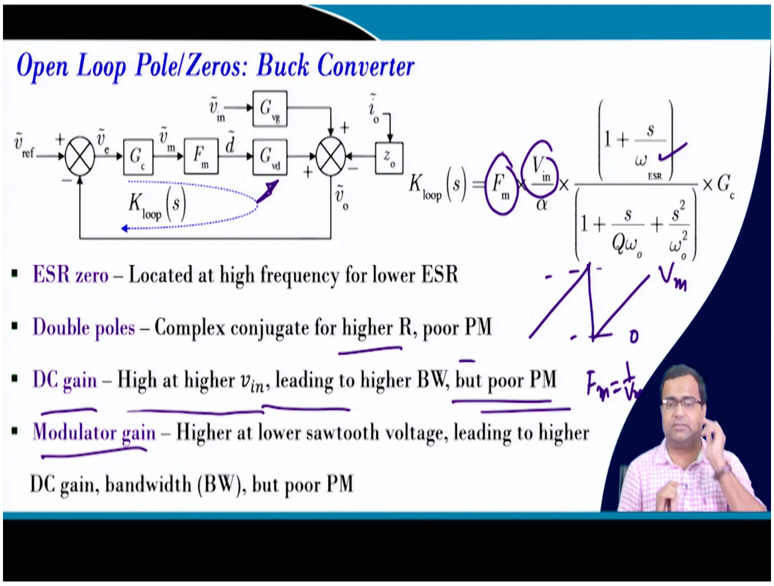

So, this is a loop transfer function. It consist of the open-loop pole; open loop transfer function control to output transfer function. Loop transfer function, so we have an ESR zero here and if we take as low ESR, it will be at high frequency. We have double poles; generally, they are complex conjugate, if the load resistance is high.

So, it will lead to a poor phase margin. Then, we have a high DC gain if we want; that means, we want to shift up the gain plot, then the bandwidth can be increased. But it will lead to poor phase margin and since the DC gain dependent on the input voltage, that is a drawback of the voltage mode control.

And you know if we apply input voltage feed forward which we discuss in week I think week 3 that feed forward technique and if we use the input voltage feed forward, then we can make the loop gain independent of input voltage and then, we can you know accordingly design the loop gain. But if the loop gain is high, it will lead to a poor phase margin.

So, we need to you know anticipate by suitable compensation modulator gain which is 1 by V m. So, if you take a lower voltage, that means, I am talking about this peak-to-peak voltage. So, this is my V m; this is 0 and the modulator gain is 1 by V m. So, if the V m is small, modulator gain is will large. When the modulator gain is large, then it will shift up the DC gain of the loop. So, it can increase the bandwidth, but at the cost of poor phase margin ok.

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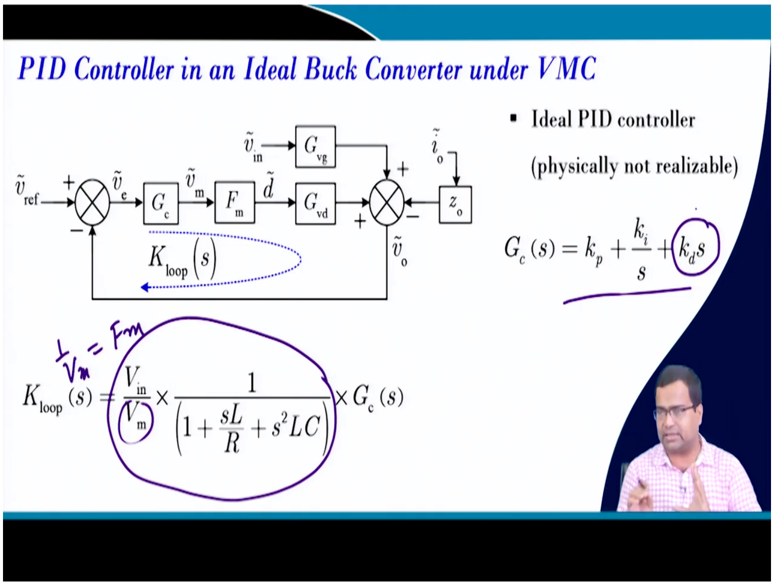

Now, we are talking about a PID controller in an ideal buck converter. So, if you take an ideal buck converter, then the transfer function become simple, very simple. And this V m, 1 by V m is nothing but our F m ok. Now, ideal PID controller like this, but it is physically not realizable because this derivative action, pure derivative, cannot be realized because even if you use an op-amp, op-amp has a finite bandwidth.

So, naturally, it will give rise to a band limited dB derivative action and we will discuss.

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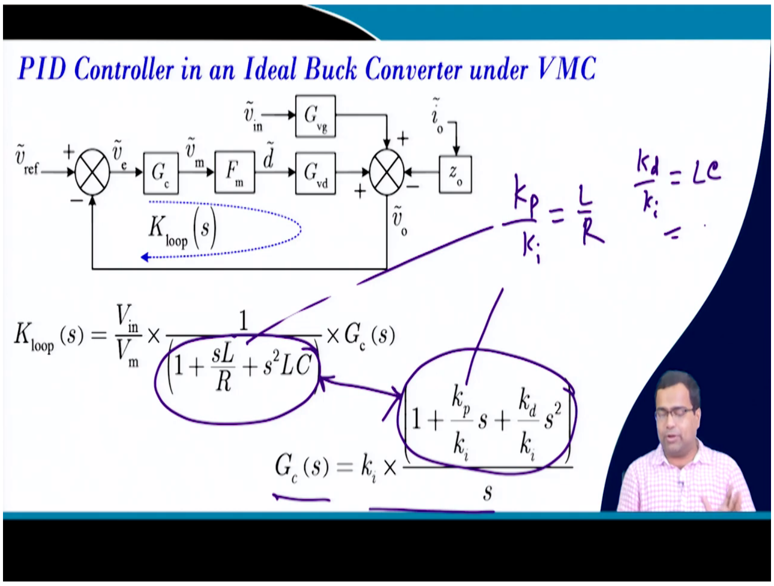

Now, if you want to compensate this, then what we should do? The controller transfer function written like this. It can be written, we need to cancel using this. Suppose we are going for stable pole zero cancellation and we want to cancel this; that means, we want to cancel these two terms and if you do that cancellation, then the polynomial from here, you can find that k p by k i which is this term will be equal to this term right, it is L by R. Similarly, k d by k i will be equal to LC.

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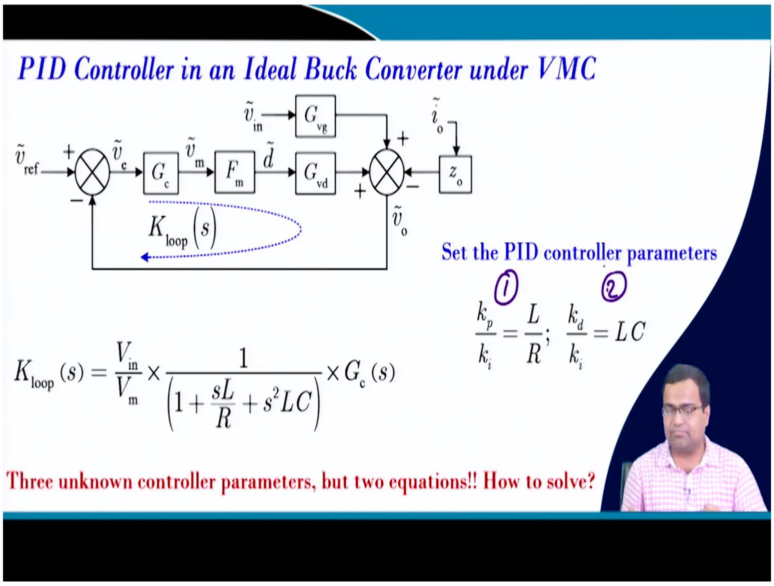

But now, we have two equations here; equation 1, equation 2. But we have three unknown k p, k i, k d. So, how to solve?

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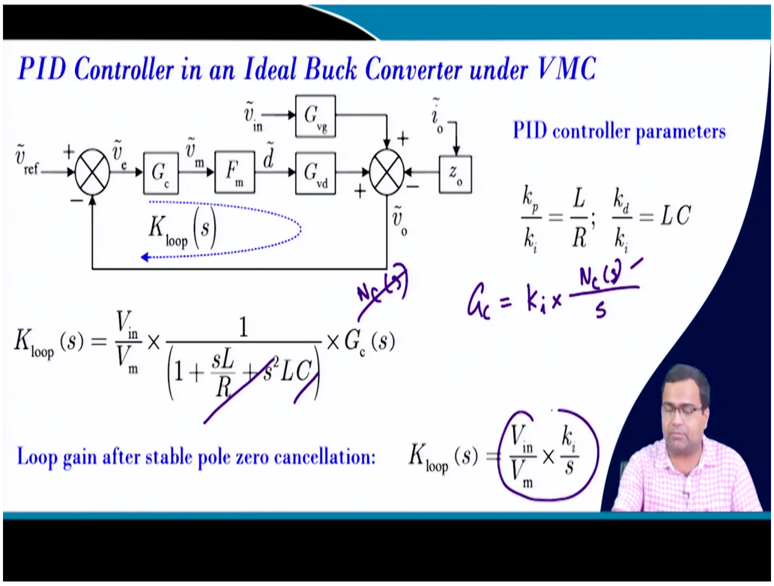

Now, once you set this compensation, our loop gain because we are cancelling this pole with the controller zero; controller zero, we are cancelling. Then, the compensator will have you know if you go back what was our compensator structure? It was k i into the controller numerator divided by s. So, this term is getting cancel with this term. So, we will end up with k i V in V m, this is the term.

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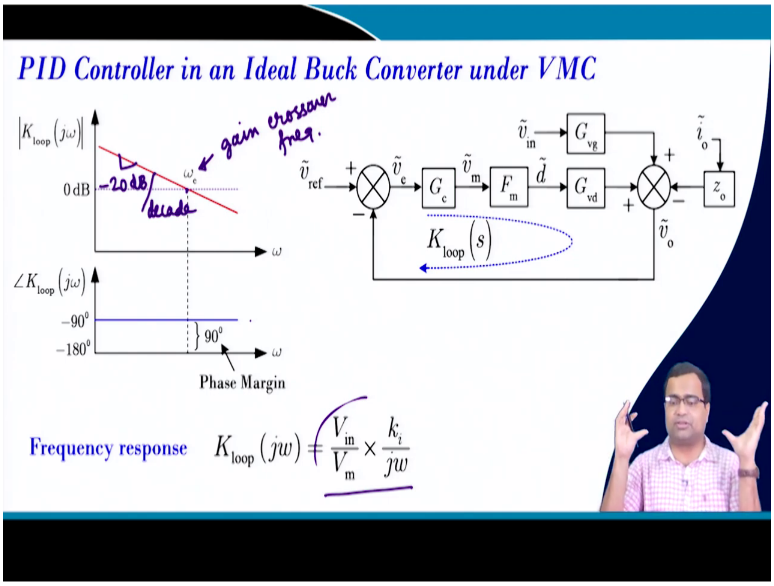

And if you derive the frequency response; that means, s equal to j omega, then this will be the transfer function and if we plot the frequency response that is the Bode plot, then this will be minus 20 dB per decade minus 20 dB per decade. And this point is called as the gain crossover frequency.

And this will be actually the closed-loop bandwidth, the gain crossover frequency ok and since, it is a first order, only single pole, so this will lead to 90 degree phase margin because it is a first order system. So, the closed loop will also be a first order system, ok.

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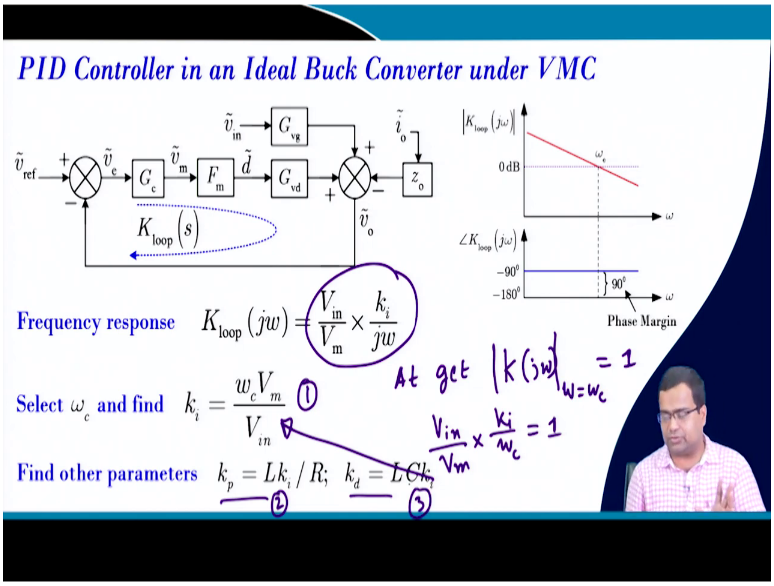

So, that means, the frequency response I can select that means, if I at gain crossover frequency; that means, at gain crossover frequency, our k j omega if I take amplitude at gain crossover frequency, it is unity. And if we can compute from here; that means, our v in by V m into k i by omega c is equal to 1 and from here, we are getting integral value ok. So, you can set it and other parameters also we have. Now, we have another equation 2, equation 3. So, you have three equations, three unknown we can solve it.

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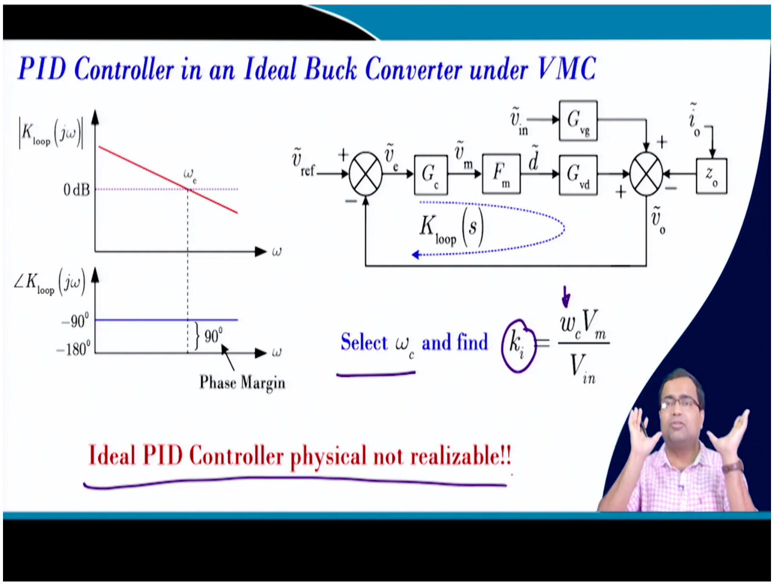

k i; so, now k i by if we want to increase the gain crossover frequency, then we need to increase the integral gain, simply the integral gain. But ideal PID controller is not physically realizable and, of course, we started with an ideal buck converter, ideal buck converter also does not exist.

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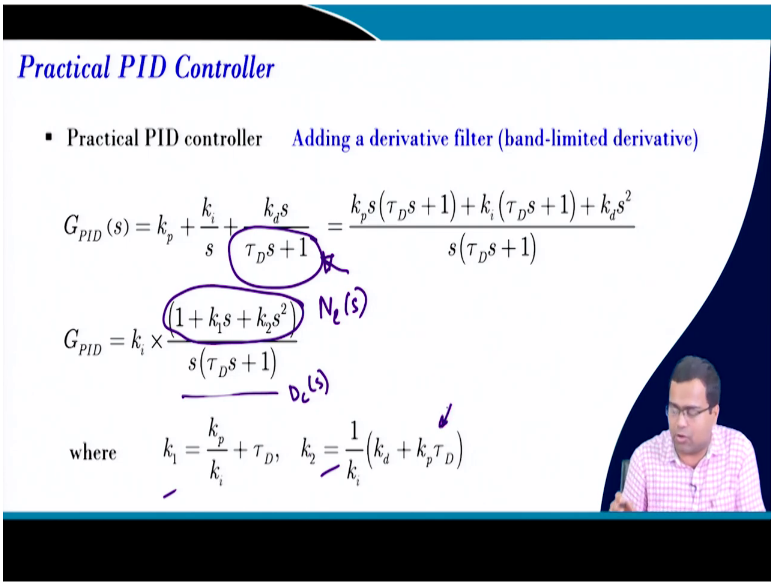

So, now we are talking about the practical PID controller. In a practical PID controller, we generally use a derivative filter and it is the derivative filter, and this comes either we can put an intentional derivative filter or it can be the part of the op-amp because op-amp has also band limited.

It bandwidth is limited. But we generally because we take an op-amp with a very high bandwidth, so we place this derivative pole as filter pole as per our wish. Because we need to choose this pole in order to meet certain requirement. So, that is why it is our design that where are you going to place the derivative filter pole.

So, the structure of this PID controller, if we take generic structure. So, this controller, I can say again the numerator of the controller which is nothing but it is derived from here and this is our denominator of the controller. So, this is my controller denominator. So, we can find out what is k 1, k 2 in terms of k p, k i, k d and there is now tau d term.

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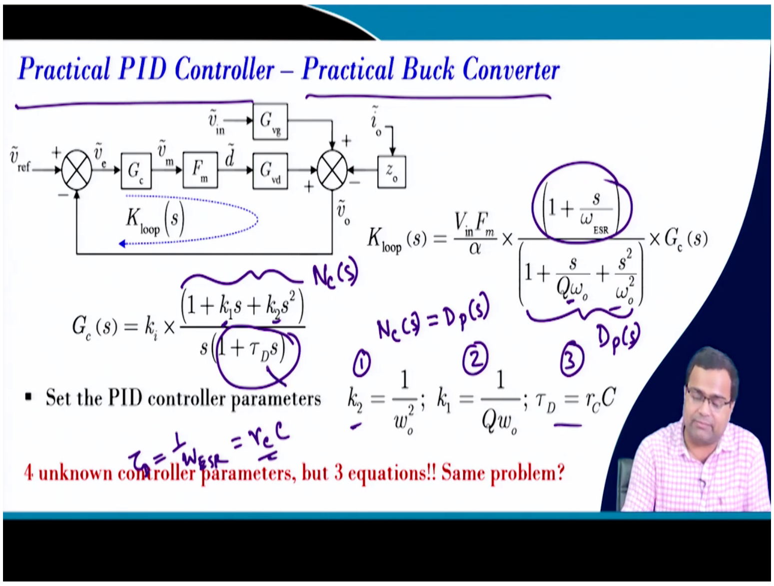

Now, again, we want to we are talking about a practical PID controller which is physically realizable and a practical buck converter which is you know actual experimental setup or actual implementation. So, in the loop gain, our first objective that means, we are again going for stable pole zero cancellation.

If this is our controller polynomial, numerator polynomial and this is our plan denominator polynomial. So, first thing we want to do, the controller numerator polynomial is set to the plan denominator polynomial ok. That means they cancel and if you do that, then k 1 here will be equal to 1 by this k 2 here will be equal to 1 by omega 0.

And we also want to set that tau d should be it should cancel the ESR zero; this ESR zero. So, this controller pole is used to cancel this ESR zero; that means, here what is ESR zero? It is 1 by r c into c. So, it is simply r c into c that is here. So, here we have how many equations? 1, 2, 3, but how many unknowns? The PID controller, we unknown are k p, k i, kd three plus 1 derivative time constant.

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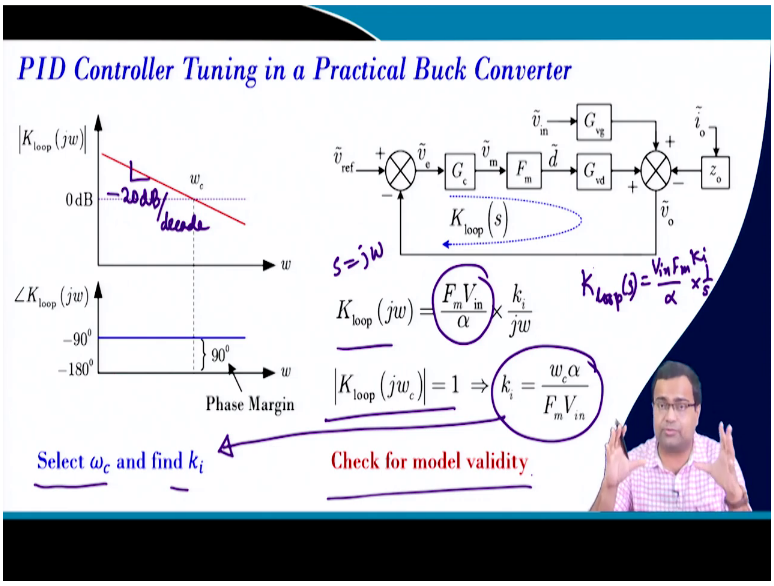

V in F m alpha k i by s, and if you substitute s equal to j omega, then, so because our what was our K of s; K loop of s? It was V in F m alpha 1 by s. So, we replace s equal to 1 j omega ok. There is also k i k i. Now, same at gain crossover frequency, it is 1. So, from here, we can set k i equal to this value and again, the loop transfer function will be a first order, just like a pure integrator.

It will have minus 20 dB per decade ok and phase margin is 90 degrees. So, if we select the gain crossover frequency, then you can find out k i by using this formula. We can find out k i by using this formula and then, we need to check for model validity ok. So, in order to check the model validity, let us go to MATLAB because we want to check using MATLAB transient simulation.

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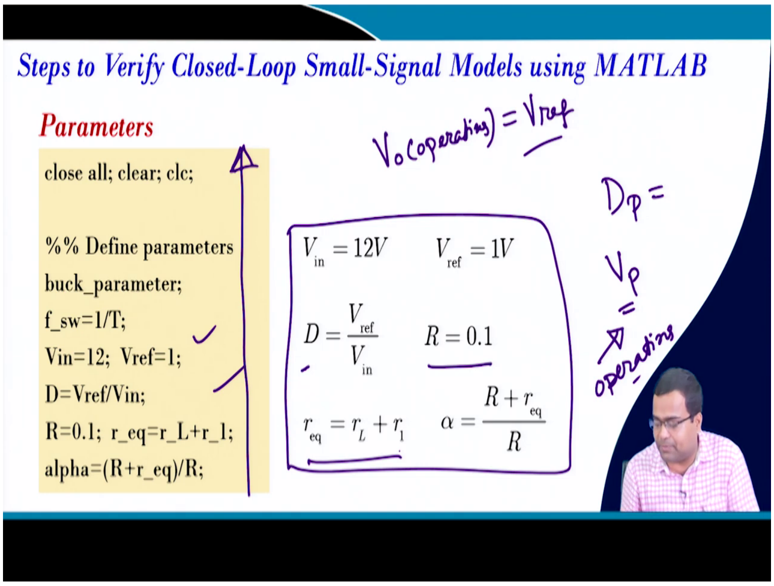

So, now, since we have already discussed in lecture number 30, the step by step all procedure how to you know this is our MATLAB script file ok. So, I am just you know trying to you know just summarize this. We are not going each and every line. So, these things are already discussed in that lecture number 13 and this all r equivalent etcetera is explained. But now, here, we do not need a practical duty ratio.

Why? Because in the earlier case, we need to have a practical voltage because it was an open loop. So, in order to because we obtain the AC simulation transient simulation by from a small-signal and we wanted to add that AC small-signal response with the steady state operating point, DC operating point. For that, this was our operating voltage.

So, this was our operating voltage right. So, in an open loop, you need to find this operating voltage which depends on the load current, duty ratio and other thing right. So, that is why we derive. But here, we are doing closed loop control and we have an integrator. So, we can assume that our operating point V 0, operating point operating point is nothing but V ref, where we are setting because we are using an integral gain.

And you can assume that average will come to V ref within a reasonable amount of time. Though they are defined in terms of you know limit t tends to infinity, but we will get close to the same value within a certain finite time. And these things, we have already explained you know duty ratio open loop and load resistance is set 0.1 Ohm. Then, R equivalent we can obtain, alpha.

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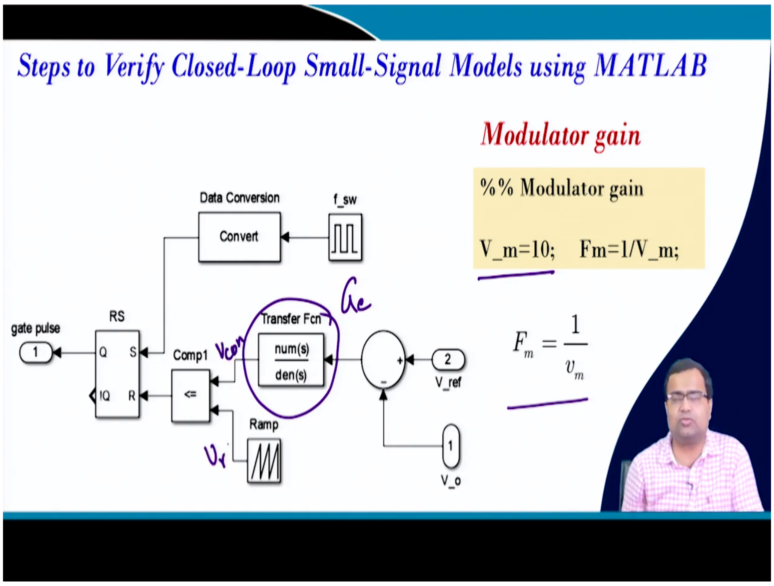

Now, the modulator gain V m took 10; 1 by V m is a modulator gain, and this is the implementation we did it. This is a closed loop. Now, this is your controller, and this is our controller and this is our V con and this is our ramp voltage. So, this all we have discussed.

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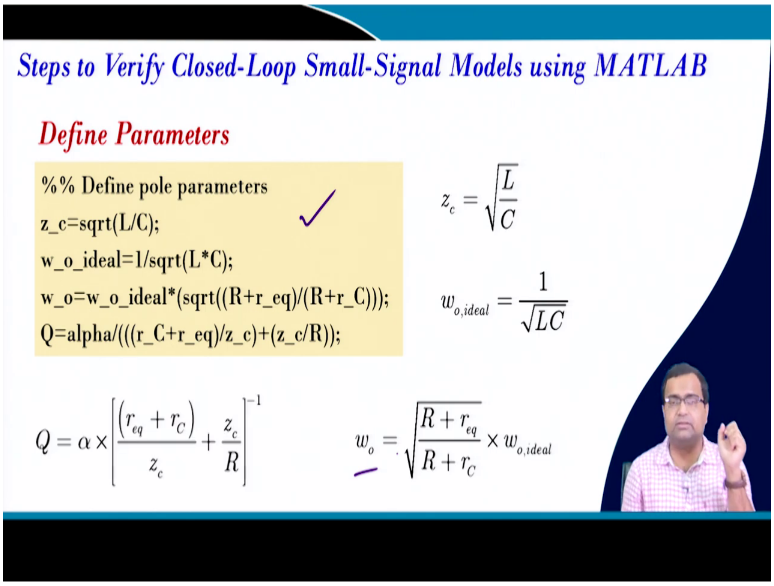

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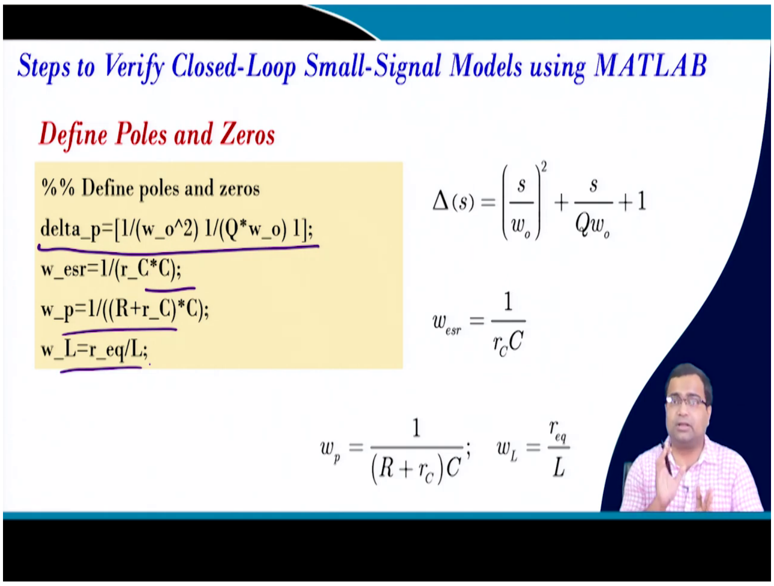

Now, we want to double pole all these parameters; we have already explained earlier; the characteristic impedance, ideal, practical, you know natural frequency, then the Q factor. We have also defined earlier the poles and zeros. So, delta p is my open-loop pole. What is that?

Delta p, we have discussed, and this is we have plugged in into MATLAB and esr zero; then another pole omega L; this will be needed for output impedance. esr zero, the other poles also we have written. So, this thing we have repeated in lecture number 30.

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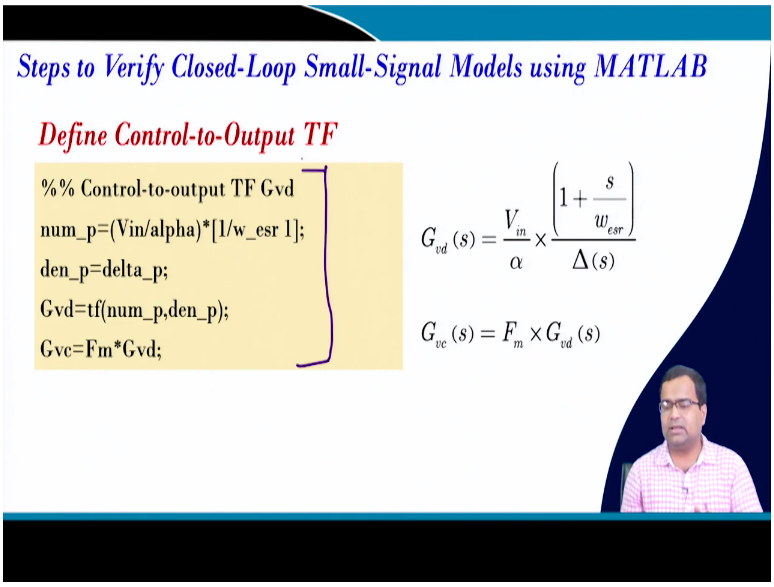

We have defined the open loop control to output transfer function like this. This also we have discussed in that lecture number 30.

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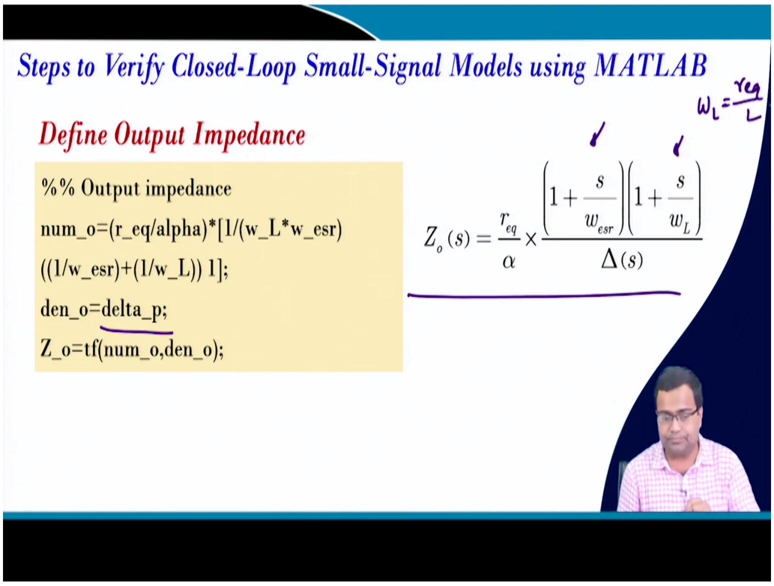

Open loop output impedance, we have discussed lecture number 30, how to write with transfer function. So, these are all explained. You know the denominator pole is common delta, and it has two zero, one due to ESR and another due to the DCR equivalent resistance of the inductor and RDS 1. So, here omega L. What is omega L? Omega L is nothing but r equivalent by L ok.

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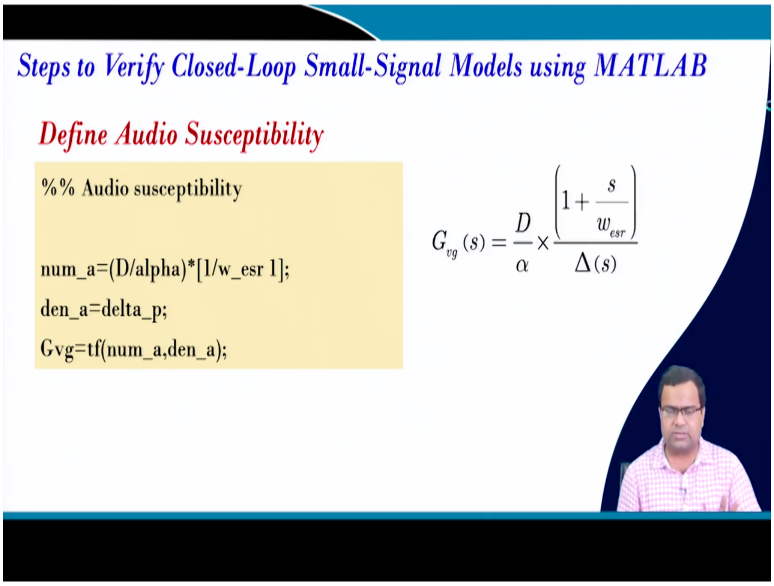

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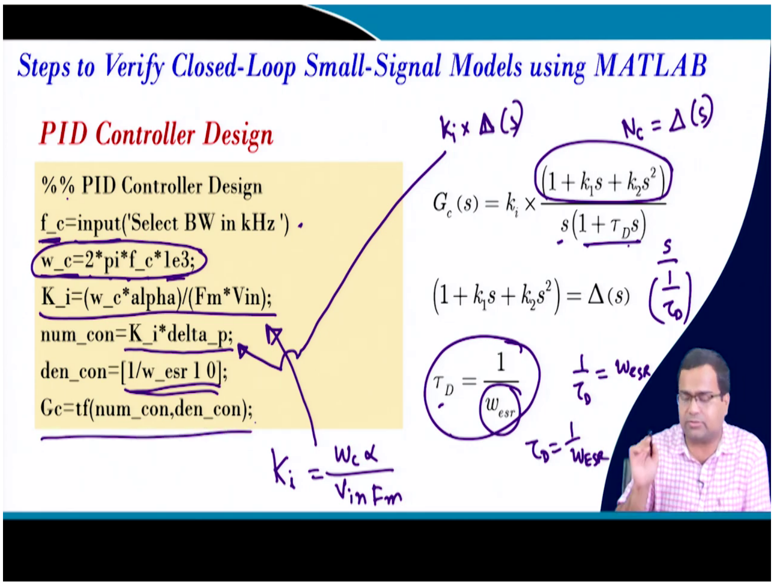

Then, audio susceptibility, we have also discussed open loop audio susceptibility. Now, we are going for a closed loop. So, from this point, we are now adding new thing. So, first we want to design a PID controller.

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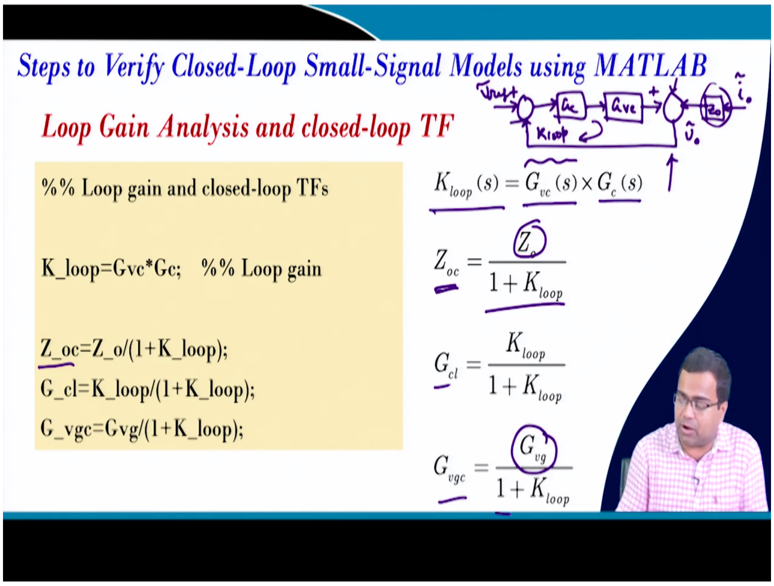

And we have discussed in the PID controller, what was if we go back to our PID controller, what was our k i? I mean, you know if you go back, yeah our k i is omega c alpha by f m V in ok. So, that means, here if we go to PID controller, what is our k i? k i is omega c alpha by V in F m ok. So, now, if you check initially, it will ask for your crossover frequency, what crossover frequency you are going to set. It is user choice.

So, it will ask for the input and I will show you in the actual MATLAB. Then, this frequency, I will ask in kilohertz ok. So, it has to convert into radian per second. So, it is 2 pi f c into one-third because we are asking in kilohertz. So, we have to convert into radian ok.

Then, k I this equation, we are plugging from here ok and the numerator coefficient is nothing but of the controller numerator is what? So, this is a controller numerator N of c is equal to what? It is our delta of s that is the denominator of the plant, which is a delta p ok. So, your overall control numerator is k i multiplied by that means, delta s. So, this is exactly what is here ok. What is denominator?

Denominator, we want to take this controller; that means, there is one pole right. There are two poles; one pole at origin, another pole will be s by 1 by tau D like this right, this is our pole. So, the tau D is esr zero because we want to cancel; that means, you are taking 1 by tau D to cancel esr zero. So, here tau D is nothing but 1 by ESR zero. So, this is exactly here and then, the controller transfer function.

Next, what is the loop transfer function? It is the transfer function of the control to output transfer function, which includes the modulator gain into the controller right. Then, what is our closed loop output impedance? So, if you go back to our you know plan model. So, suppose this is our G vc, and this is our G c ok and this is our open loop output impedance ok and this is our v 0.

The v perturbation 0 minus and this is my loop transfer function k loop. That means my closed loop output impedance will be open loop output impedance divided by 1 plus loop transfer function. Similarly, closed loop transfer function will be loop transfer function by 1 plus loop transfer function, you can show from here and closed loop audio susceptibility because we have not incorporated.

So, here we will have another component audio susceptibility that can be shown as open loop audio susceptibility divided by 1 plus loop transfer function. So, this all thing we have written here.

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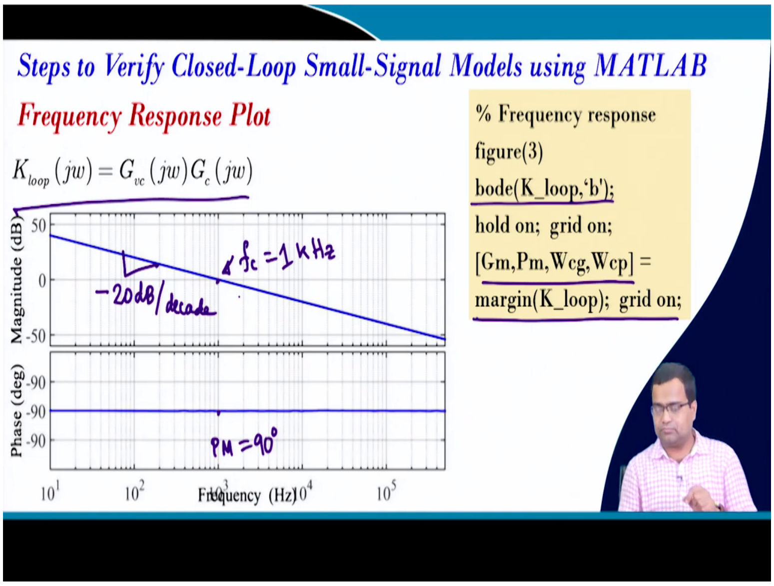

Then, we can do frequency response plot Bode plot here and we can use this. We can obtain gain margin phase margin, gain crossover frequency phase cover crossover frequency using this margin because we want to show. If we want to plug in we want to see actually Bode plot whether we are getting minus 90 degree phase margin or whatever gain crossover frequency.

So, this is our loop transfer function. This is the compensator loop transfer function. Here, we have to know what is desired. So, you see, this is our cut off frequency. So, I said here cutoff frequency to be 1 kilohertz; whereas, my switching frequency 500 kilohertz. It is too low, but I will show you why.

In a moment, we will go to that point, 1 kilohertz. So, 1 kilohertz and you see, the phase margin phase is minus 90 degrees. So, our phase margin is in this case is 90 degree here right. So, from the Bode plot, it is very clear and you can see it has like a minus 20 dB per decade ok.

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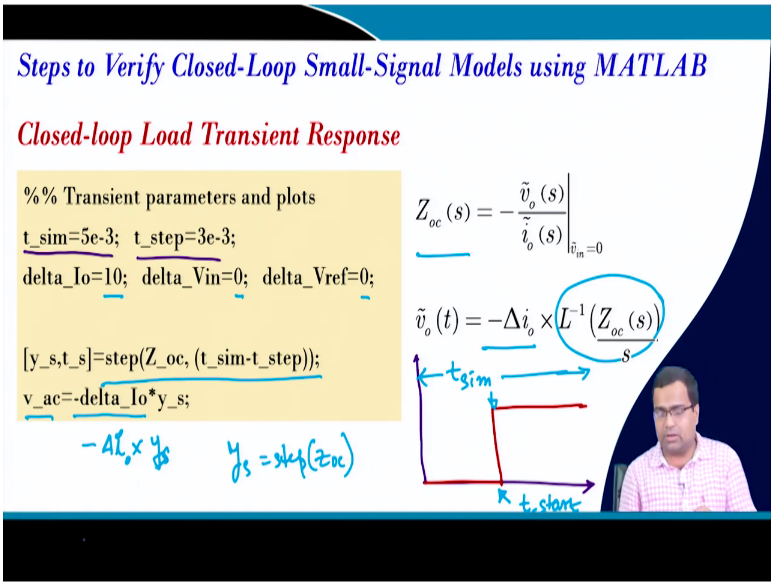

Then, loop closed loop load transient response; we want to see the load transient response under closed loop. So, again, I have explained this is a total simulation time. This is a t step ok. So, I want to show you how does it looks like. So, this is our ok response. Now, I am applying a load step transient here.

So, this time, this is my t start, this is my t start, the starting value, where the actual step is applied and this time is my t sim is a total simulation time. So, here we are applied a load step transient. And we know here, I am applying the 10 ampere load step, no step for the input voltage and the reference voltage.

So, I want to measure the load transient response by closed loop output impedance; that means, it is minus load step size and step response of the closed loop output impedance, which is the inverse Laplace. So, this is a step response of the closed loop output impedance and the AC response will be minus delta i 0; that means, minus delta i 0 into my y of s, where y of s is my AC what is my y of s? So, it is my step response of my Z oc. So, it is a unit step response ok.

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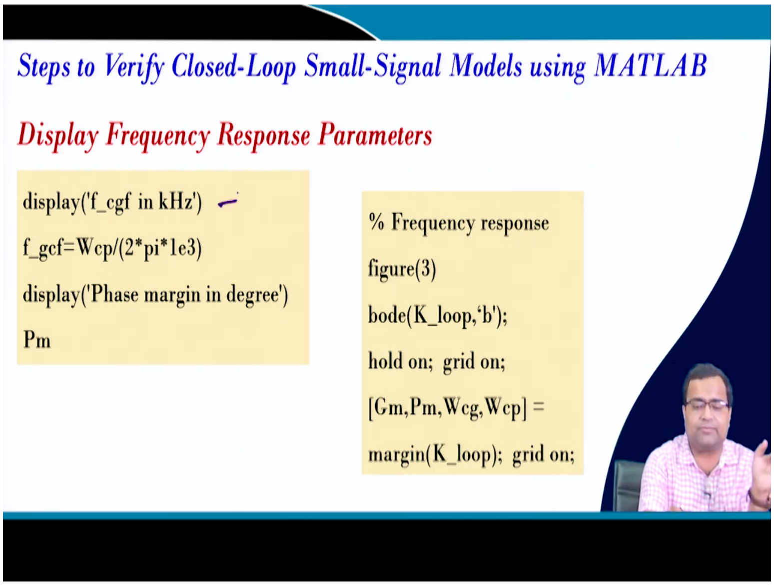

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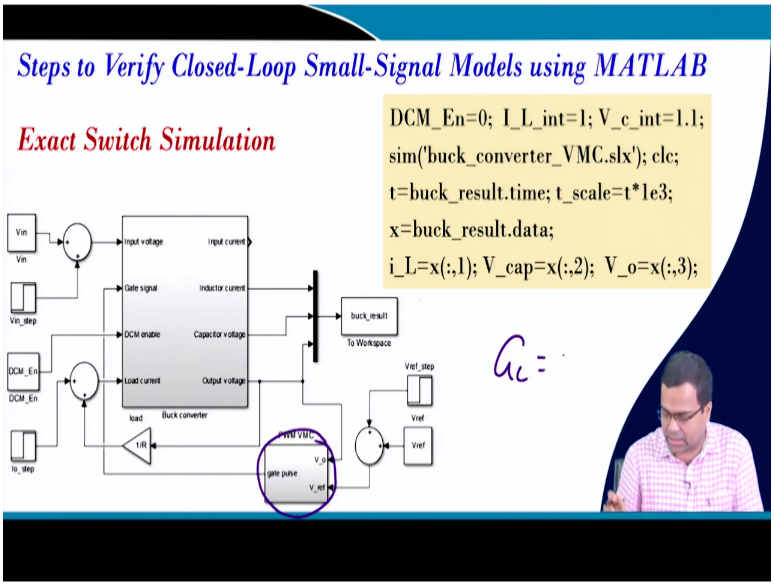

Now, so here, it can display the phase you know gain crossover frequency in terms of kilohertz you know phase crossover phase margin. So, it can show the Bode plot of the loop gain, gain margin. So, I will show exact switch simulation, we want to match ok and how to do exact switch simulation? So, since we have already computed the controller, I have shown you that this is the controller we have computed, the PID controller.

So, this controller will be this numerator coefficient, the denominator coefficient we plugged in to actual switch simulation right. So, here if we go inside that controller, inside that there will be a controller, where we are using coefficient numerator control denominator control. We will go to that very soon.

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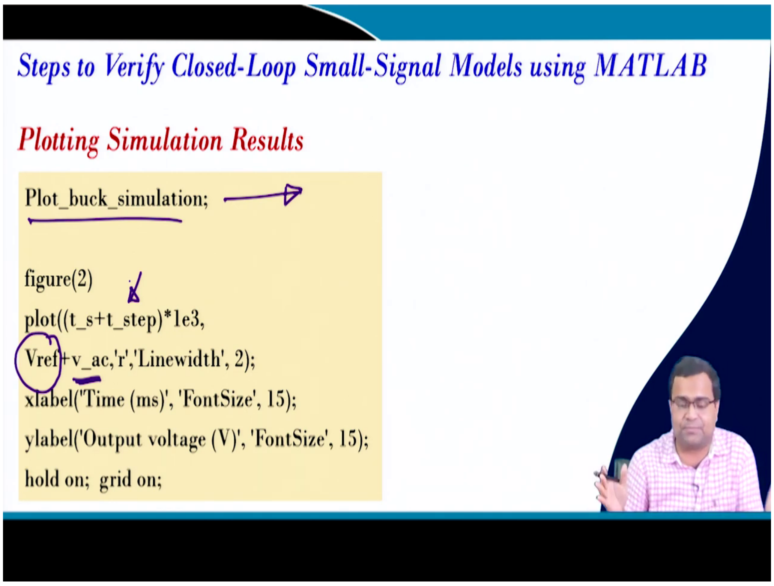

Its actual switch simulation, then I will use a plot command, I will show you what is this and then figure this is my AC simulation response, transient response of the small-signal model and I am adding the operating point which is a reference voltage. Since it is closed loop, so the operating point is V ref ok. And then, I am also adding the time offset, which is a t step because otherwise the original simulation will be from 0 to the time, we are actually extending; but we are adding the offset time.

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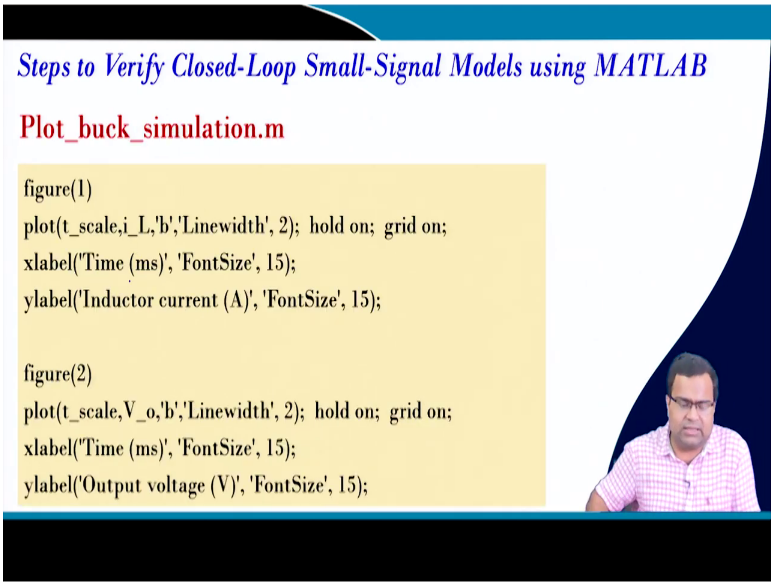

And this is my sim you know the plot dot m file which will plot inductor current and the output voltage of the actual switch simulation.

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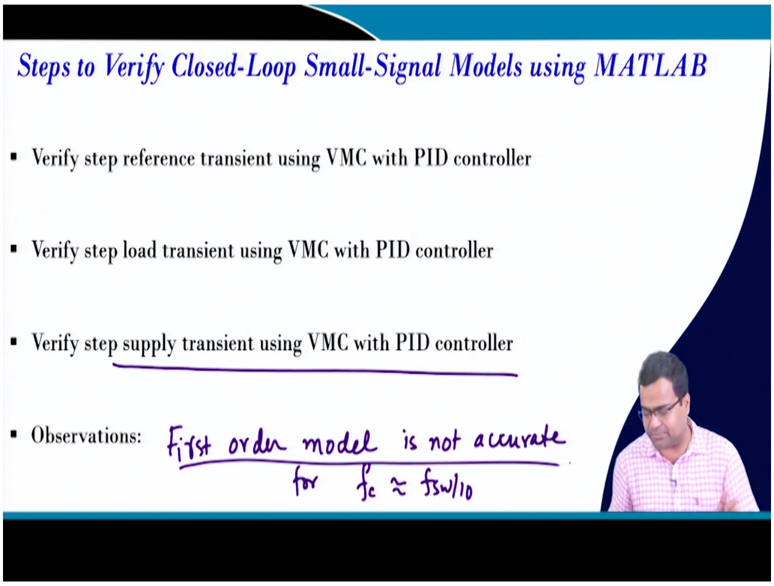

So, now we want to check, verify step reference transient using voltage mode control with PID controller, verify step load transient, verify supply transient and we need to observe.

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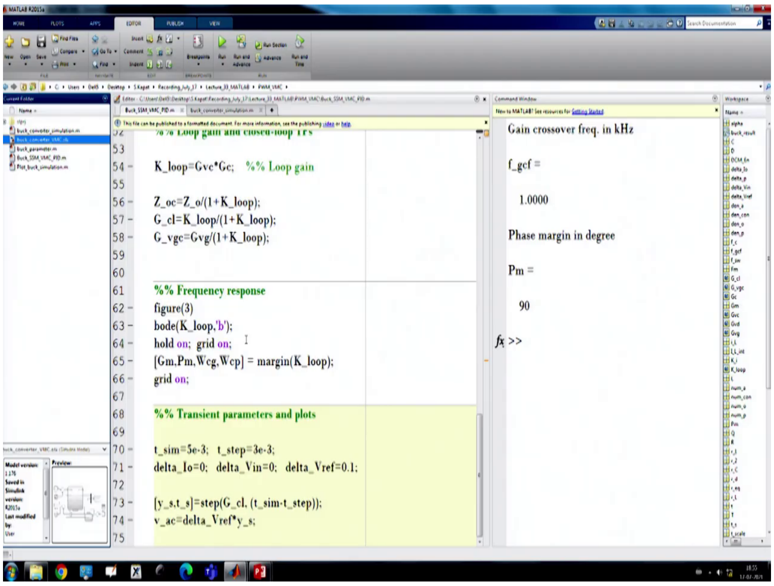

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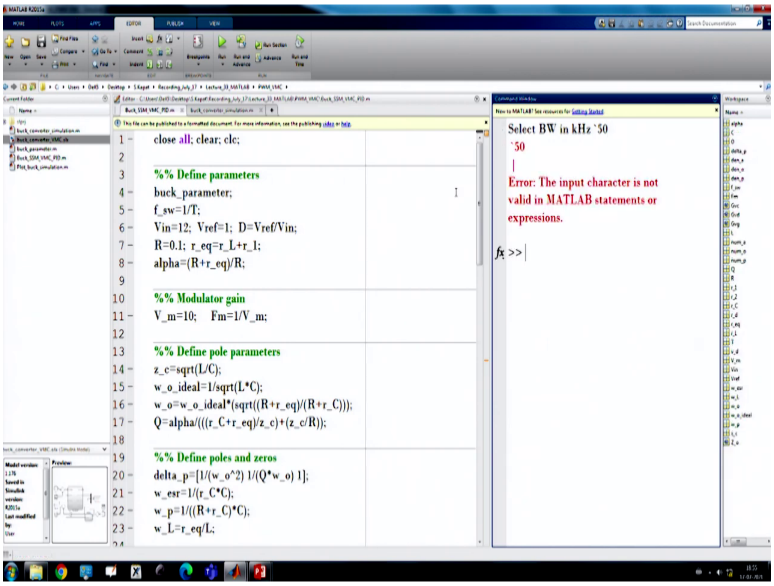

So, let us go back to our MATLAB simulation. So, the first thing we want to check is the step reference transient we have set ok. Now, here, it will ask for bandwidth. Let us see we are just setting. Let us say 500 kilohertz switching frequency. So, we want to set one-tenth; that means, 50 kilohertz is my gain crossover frequency. Sorry.

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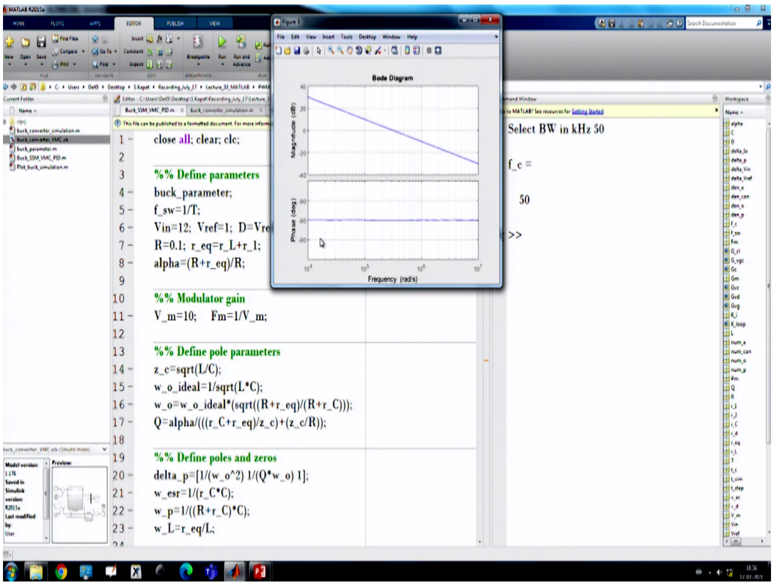

So, again if I actually ok 50 kilohertz; 50 kilohertz is the gain crossover. So, here, our gain crossover frequency is pretty high.

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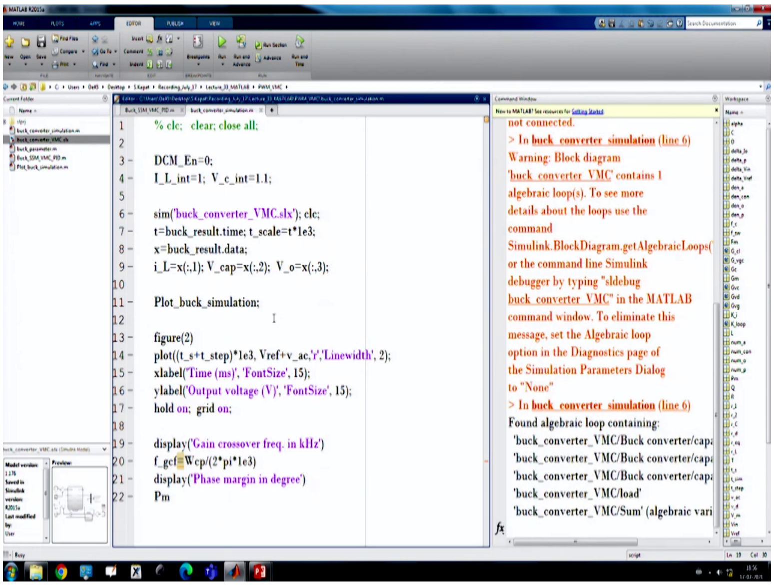

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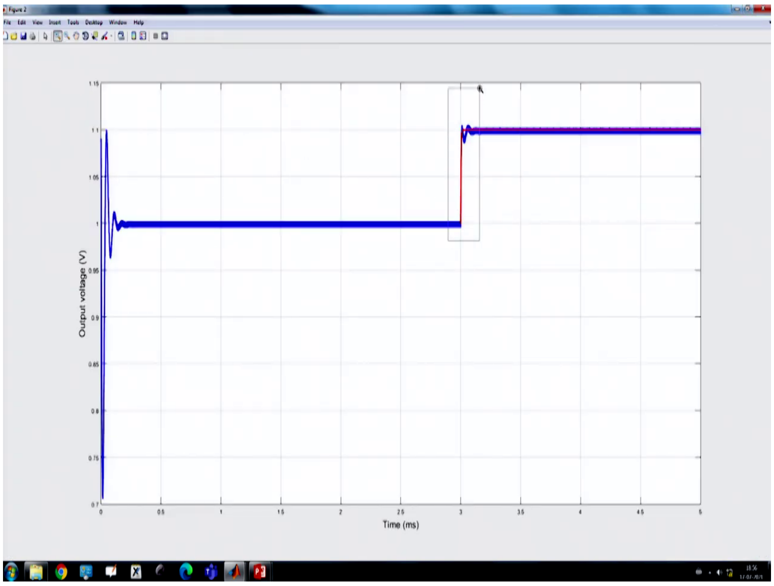

And we need to check whether our response actually matches or not. So, this we are setting yes. So, this is our gain crossover frequency for 50 kilohertz.

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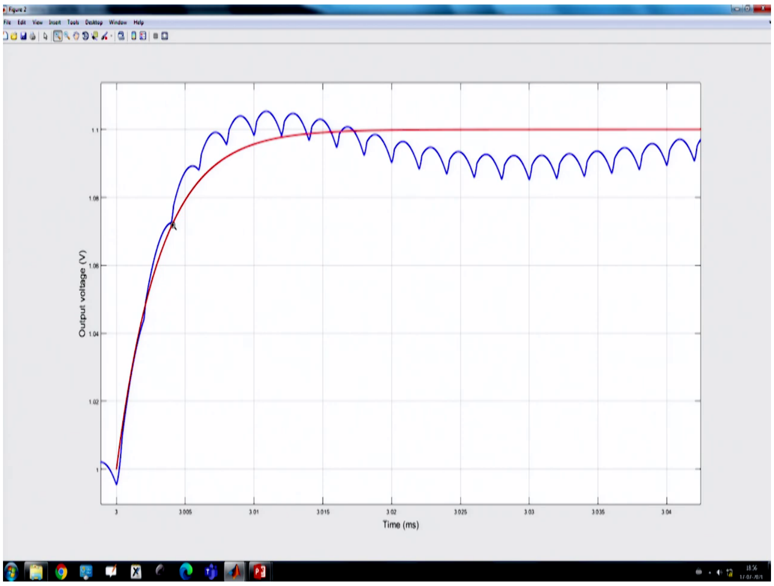

You see, the response is matching to some extent up to you know certain maybe it up to because we are trying to achieve first order system because you see the loop transfer function is simply gain by integrator; it is minus 20 degree per decade. So, the closed loop system should be a first order system; but you see actual closed loop does not actually switch step does not behave like a first order.

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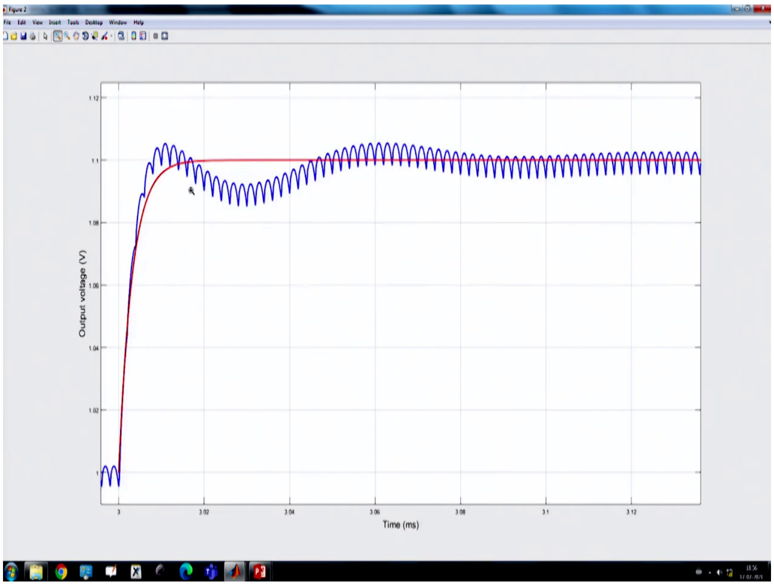

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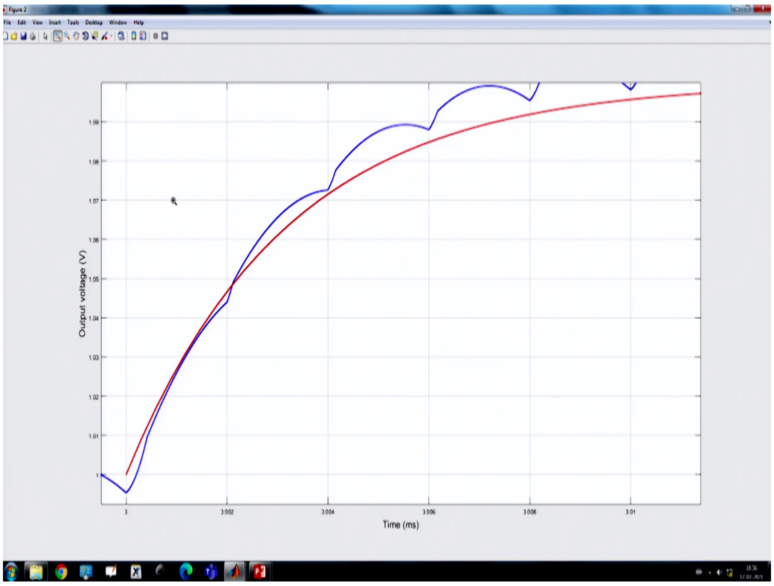

Because there is some kind of oscillatory behaviour which is not actually matching. So, that means, they are matching to some extent up to some initial stage, after that the model diverges ok. That means, if the model does not match, so we cannot predict. Whatever we predict from small-signal model, it will simply not work because your actual switch model is deviating. What is the reason? If we reduce the bandwidth, we run again; we reduce the bandwidth to let us say 10 kilohertz.

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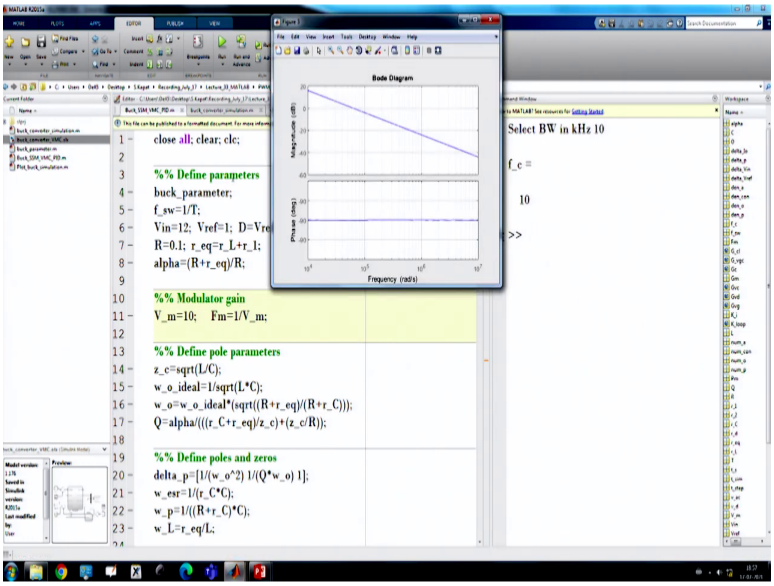

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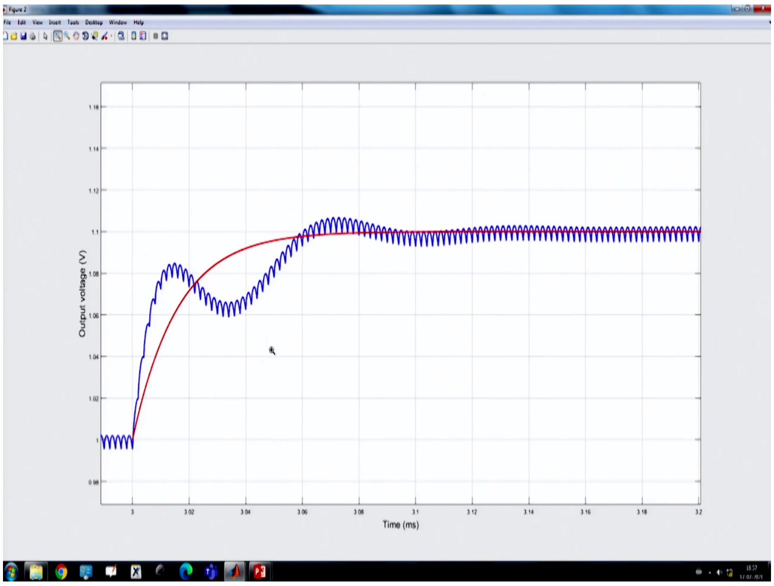

Now, we have reduced; earlier, it was 50 kilohertz, now reduced 10 kilohertz, whereas, the 500 kilohertz is our switching frequency. You see, when you reduce the 10 kilohertz, the response again becomes slightly different. So, initially, it was matching the initial response, now the problem start even in between ok. So, that means, response is clearly showing, it is not perfectly matching ok. So, that mean this ok. Now, we further reduce ok.

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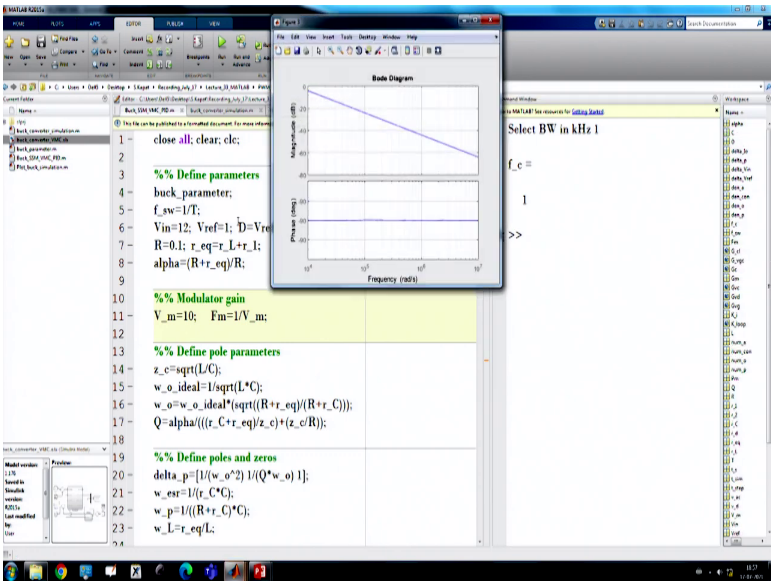

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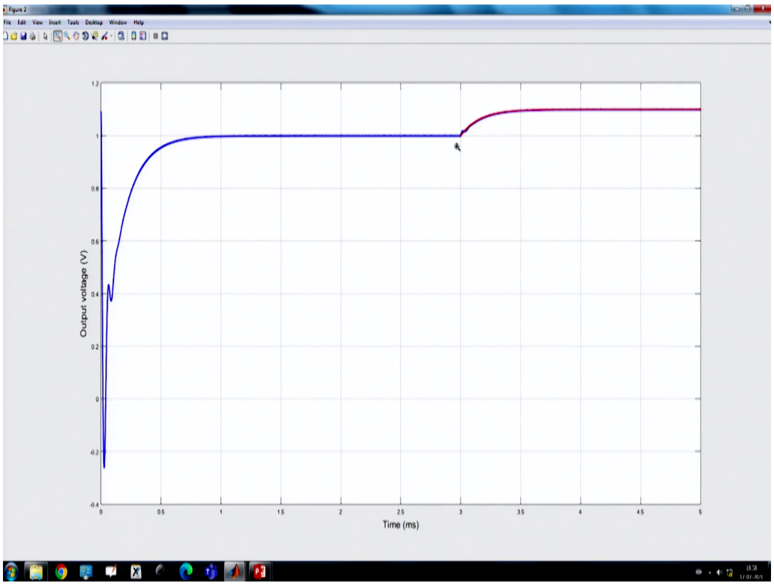

So, if you further reduce to let us say 1 kilohertz is very low, too low. Then, I want to match the switch simulation. So, it is 1 kilohertz; 1 by 500 times slower. It is very much slow.

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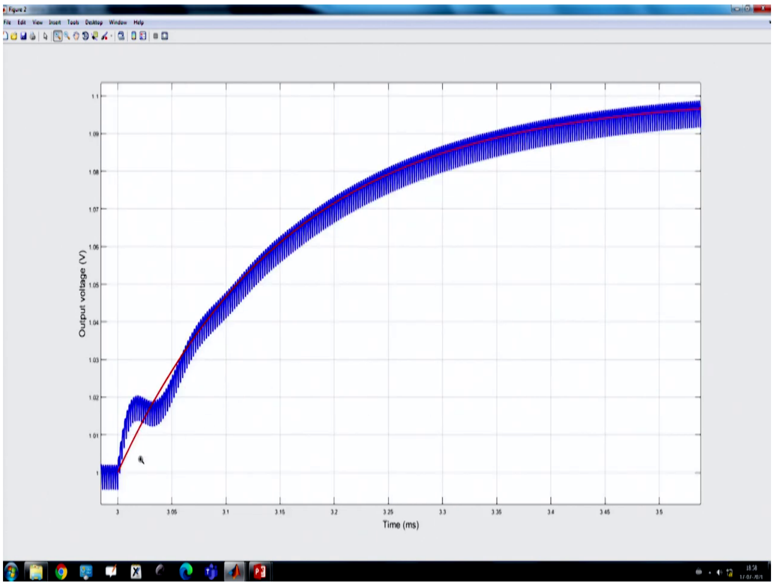

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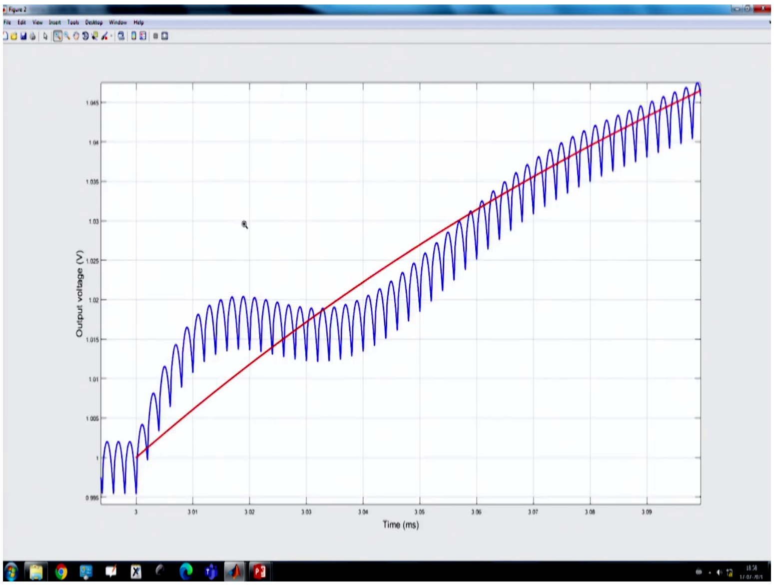

And if you see the response here, they are matching quite nicely except for the initial stage; that means, the converter is actually behaving like a first order except for the very initial stage, there is a slight deviation. That means, although we are trying to achieve first order, but actual voltage mode control, it is very hard to get first order response, at least for this simulation.

Now, so that means, there is a model limit; that means, the model limit when you go for closed loop performance, particularly for reference voltage transient, so in order to get some desirable response we need to limit the bandwidth is 1 by 500 times, which is very very slow ok. But if we go to load transient response; that means, we are going talking about load transient response.

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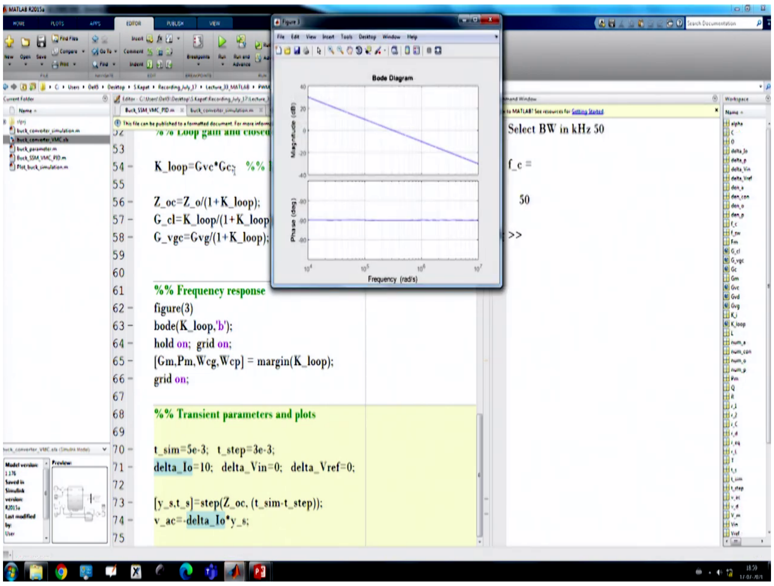

So, in the load transient response, now we are applying a load step of 10 ampere for example. And no supply voltage transient and now since we are applying load transient this should be Z oc closed loop output impedance that we have discussed and this should be multiplied by delta V 0 with a minus sign because we have discussed this. Now, again, let us start with 50 kilohertz in this case load transient response. For load transient, we want to see whether the model matches or not. This is with for load transient.

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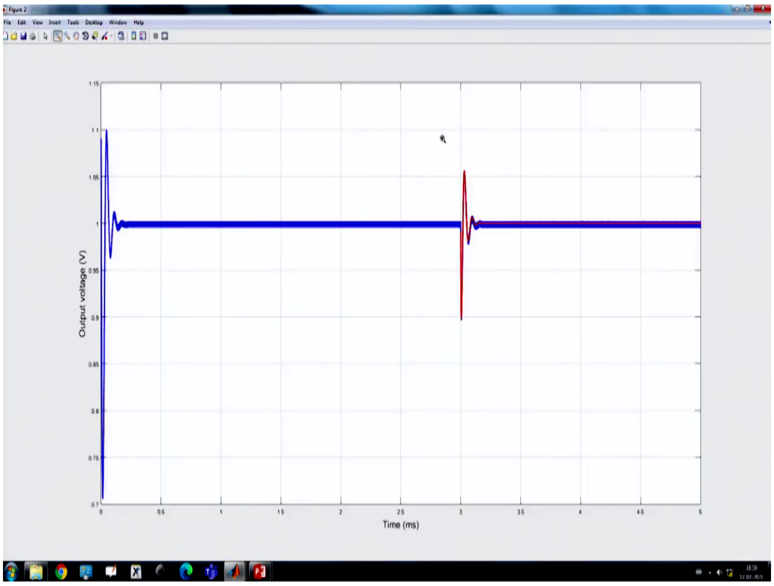

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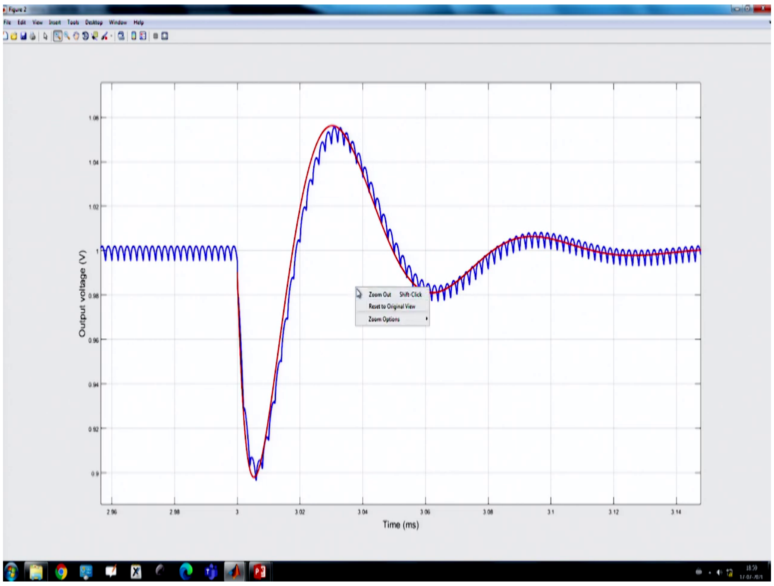

So, you see in this case the model is matching reasonably well for load transient response. There is slight deviation, but still it can capture the transient performance when the load transient is constant; that means, this model is valid close to that means, if you go this is for 50 kHz crossover frequency, where 500 kHz is switching frequency.

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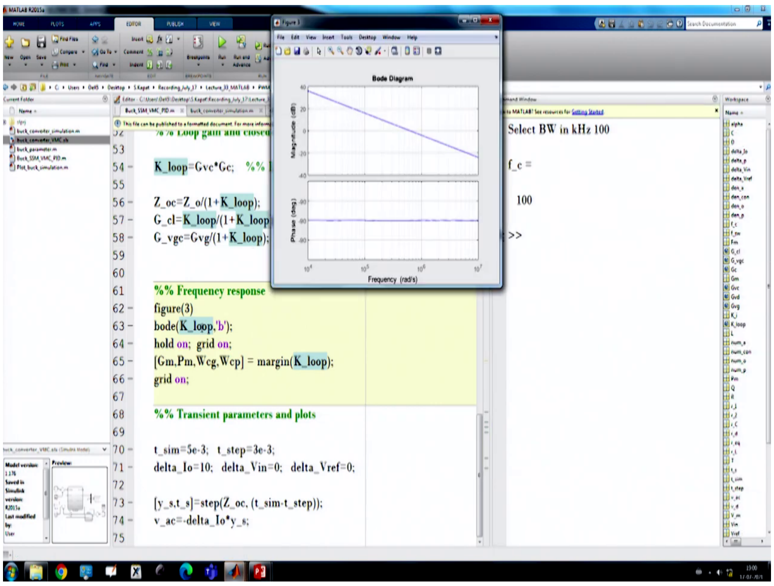

Now, if you go to let us say 100 kHz; that means, one-fifth, 100 kilohertz. Then what is our response? Is it going to match or not?

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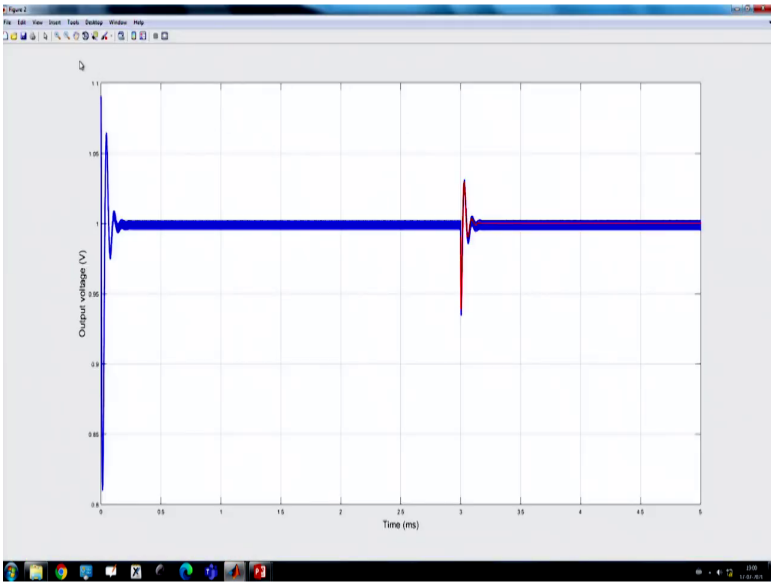

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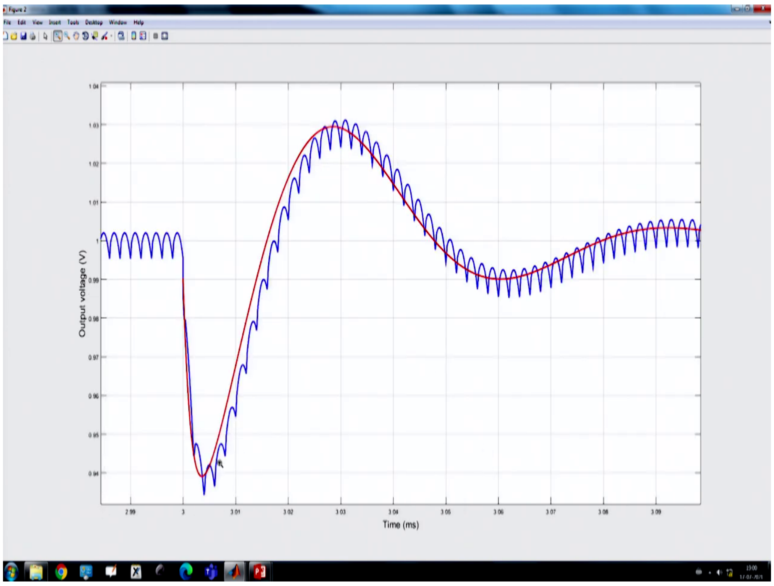

So, we are going to see the response and you will find now the response is diverting; diverging. I mean they are actual peaks is down, so the response start diverging ok. So, that means, we should not use one-fifth of the switching frequency of the bandwidth because the small-signal model is not accurately matching ok, as they are not valid.

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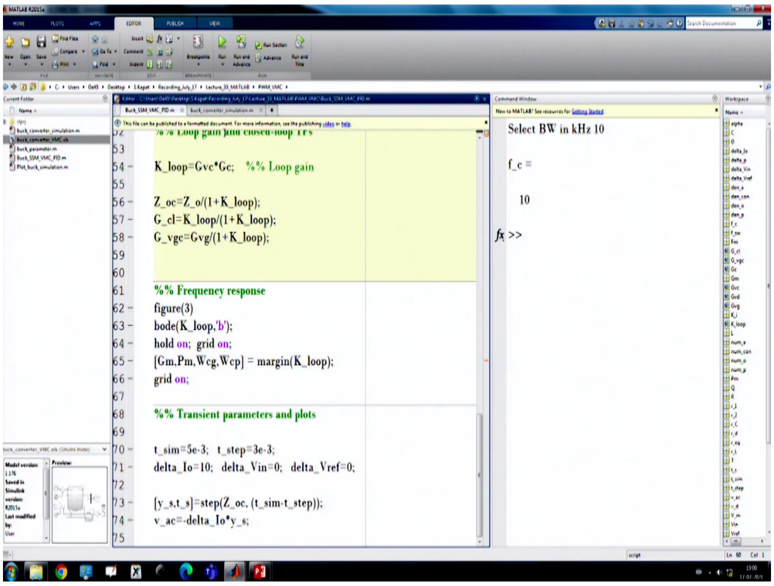

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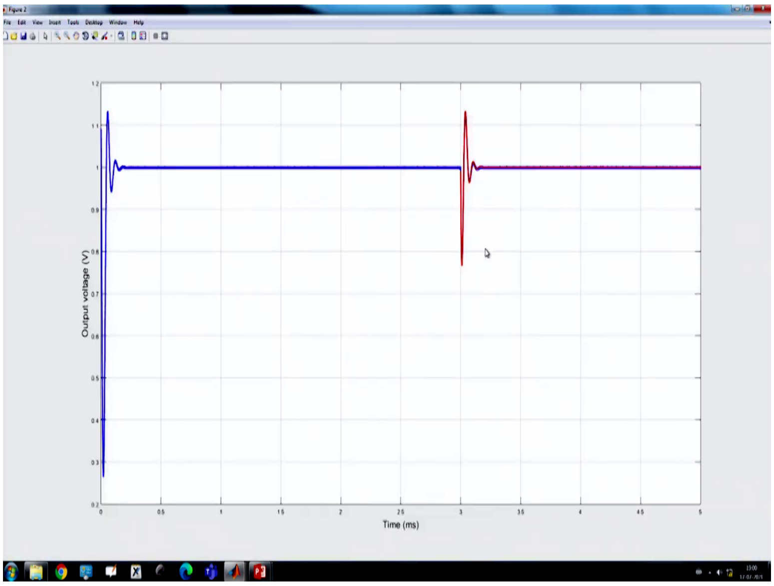

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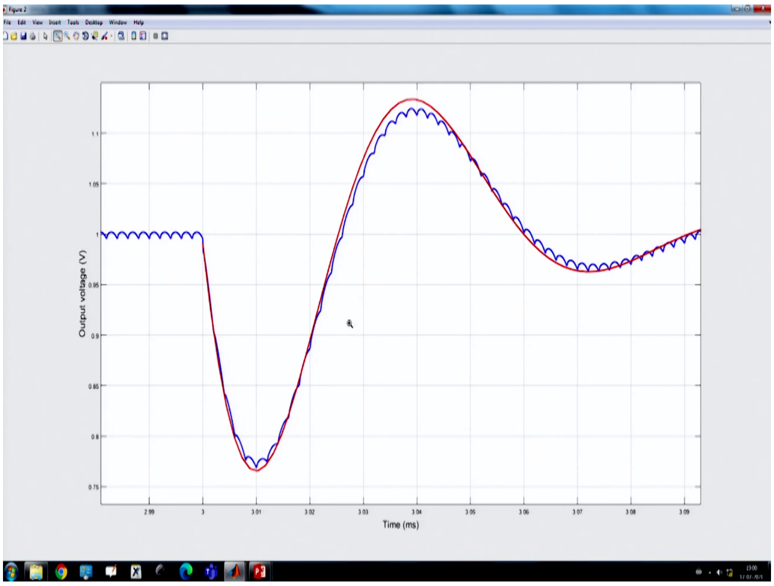

If we further reduce to one-tenth, let us say we are making one-tenth; so it is sorry 150; that means, 10 kilohertz, then we want to see how far they are matching for the load transient performance. So, in this case, you will find they are matching quite accurately, not accurately, because there is still some deviation.

So, that means, as you push and push higher and higher gain, but I can say the model matching using first order approximation is not the right solution. Once you go for type-III compensator, you will get perfect matching even one-tenth of the switching frequency. So, here because we want to achieve first order response, that is why it is not matching correctly ok.

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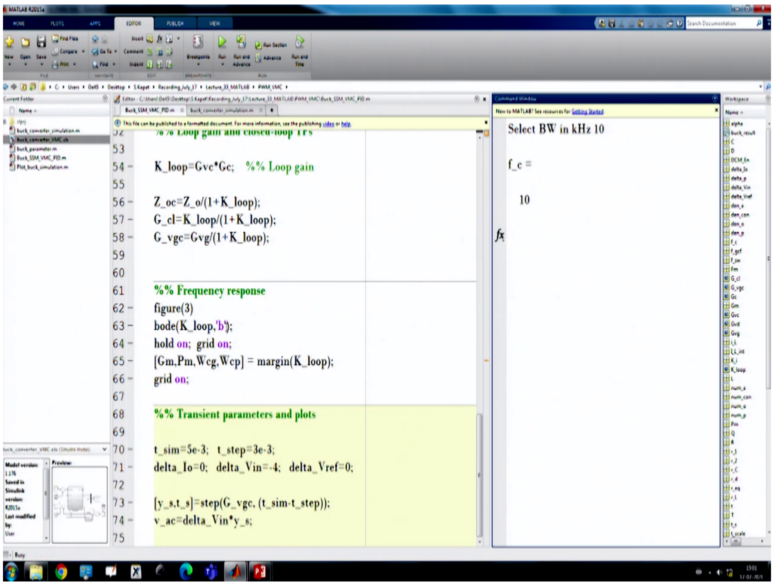

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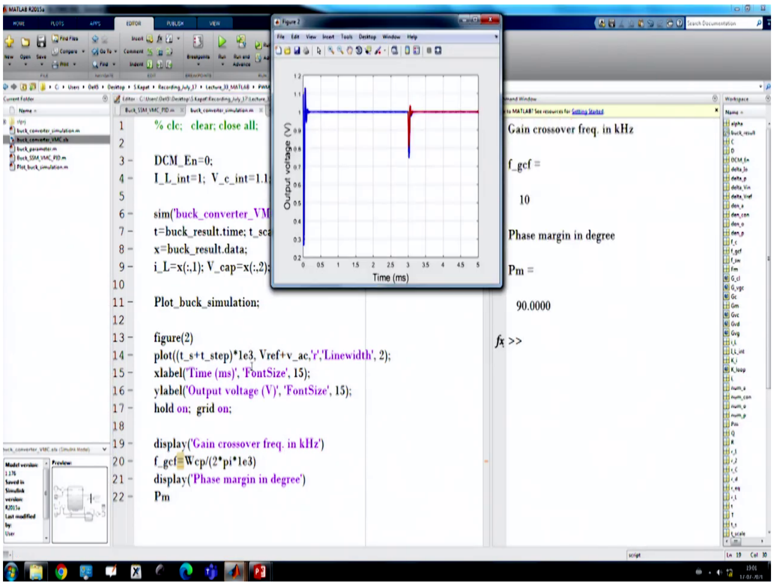

And here delta V in our load transient is 0, it is multiplied and we need to use G, so, this one ok. So, let us see what happens? So, here let us say we are setting one-ten and we are trying to match the model and see this is for supply transient whether the model match or not.

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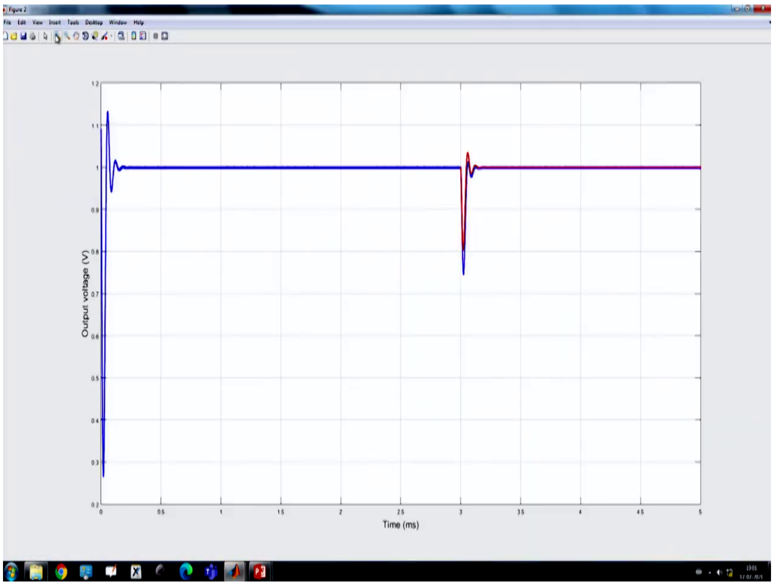

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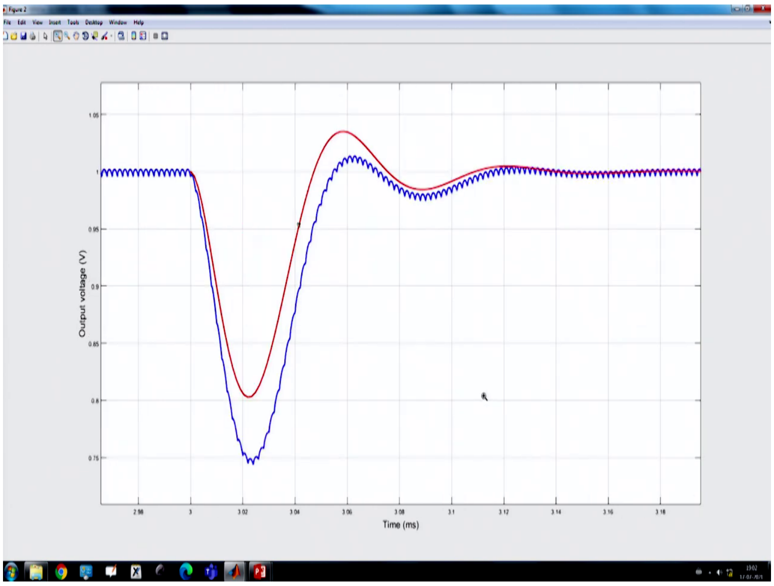

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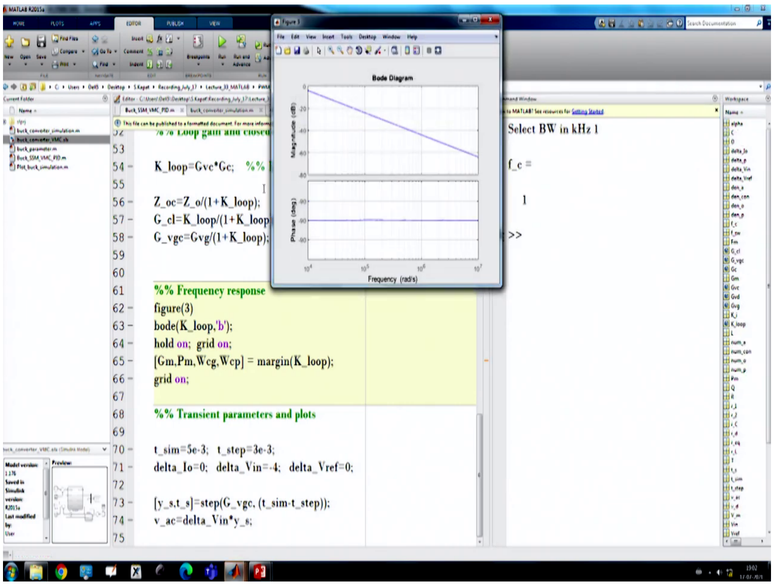

So, even for supply transient it is not matching accurately because the model start diverging because the model has to be you know if we go for very, very low like you 1 kHz, and then, let us check that how far the model matches.

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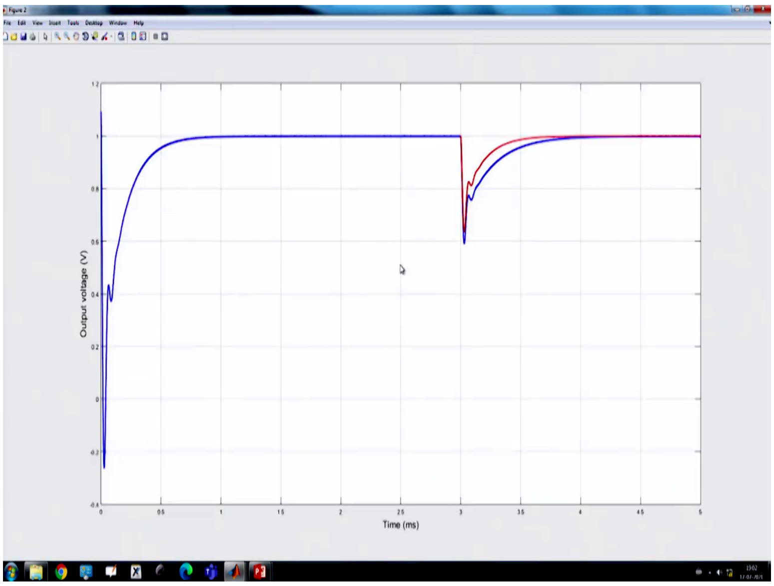

So, there is still some deviation. [FL] a supply ok. So, the supply transient also similarly, we can carry out supply transient response ok. Observation is that the first-order model is not accurate, for you know, cutoff frequency roughly around f s w by 10 and we are familiar with this; that means one-tenth of the switching.

So, first-order model is not matching. So, this may not be a good way to design; that means, this model if you use this model, we have to limit our crossover frequency to 100 of the switching frequency and actually, nobody will buy this power supply.

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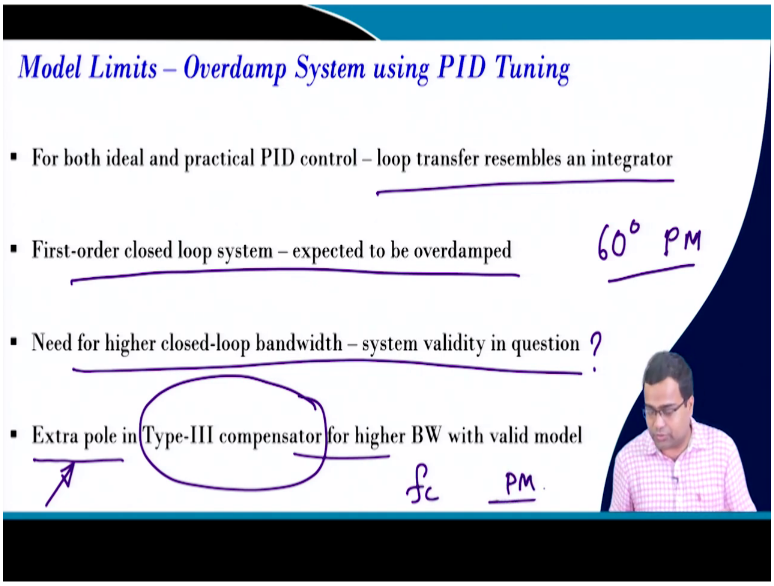

So, the model limit for overdamp PID for both ideal and practical PID controller, the loop transfer function resembles an ideal integrate an integrator. First order closed loop system expected to be overdamped; but actual loop is not matching, its validity is in question, there is a significant deviation. So, we should not use a PID controller for analog voltage mode control because we do not want the first order response, we want an additional degree of freedom. So, the extra pole has to be added with the PID controller.

And that will lead to a type-III compensator and on which using which we can get more accurate model, a very accurate model up to one-tenth of the switching frequency and there we can you know because here our objective in over damp is 90 degree phase margin, we do not need that.

Even if we have achieved close to 60 degree phase margin, it is 60 degrees; it is good enough. But if you add another pole, I will show you for a buck converter. You can independently set crossover frequency and phase margin, you can set independently. So, that will be discussed in the future class.

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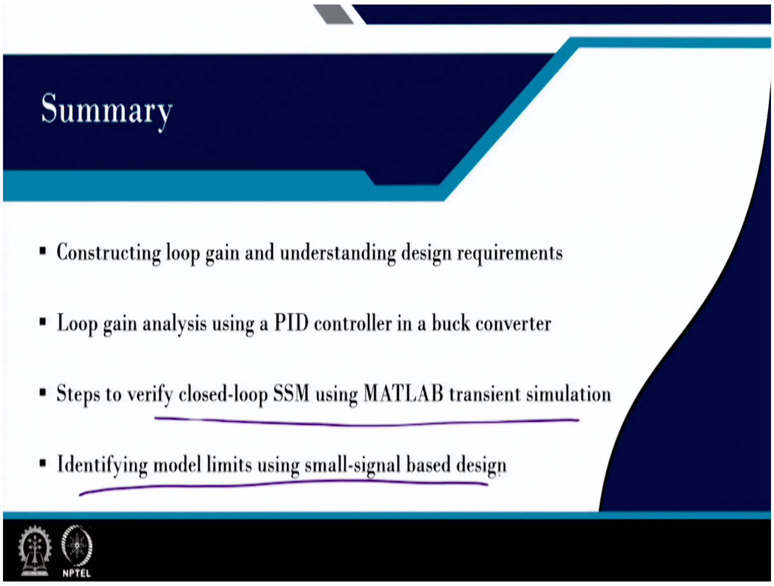

So, in summary, we have constructed the loop gain; we understood the design requirement. We have analyzed a PID controller design in a buck converter, then we have discussed step to verify the closed loop small-signal model using MATLAB transient simulation and we identified the model limit based on small-signal design and in the next lecture, we will talk about type-III compensator, where we can go even higher up to one-tenth of the switching frequency which reasonably good matching.

So, that means, we know we understood how to match the response of a system of the actual switching converter using small-signal model and we will discuss the design procedure along with the validation of model in the subsequent lecture for voltage mode control for buck and boost as well as current mode control. So, with this, I want to finish it here.

Thank you very much.