Control and Tuning Methods in Switched Mode Power Converters

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Module - 03
Fixed Frequency Control Methods
Lecture - 18
State Feedback Control

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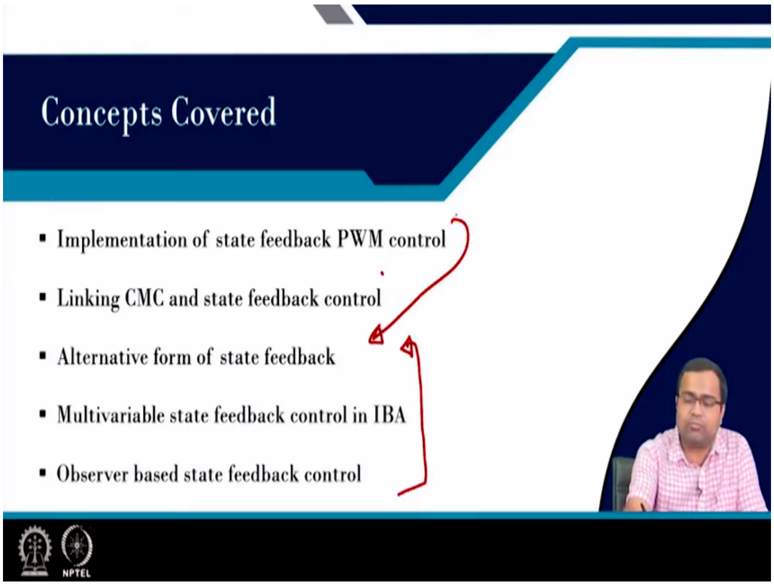

This is lecture number 18, in this lecture we are going to talk about State Feedback Control. The concept covered in this lecture implementation of state feedback PWM control, then linking current mode control and state feedback control, then alternative form of state feedback control, then multivariable state feedback control in intermediate bus architecture and the observer based state feedback control.

So, particularly this, 3 part I want to give I know just kind of glimpse because you know it will take multiple lecture to go detail into this, but just a glimpse of this, but I want to focus on this particular two aspect and want to show MATLAB simulation case study.

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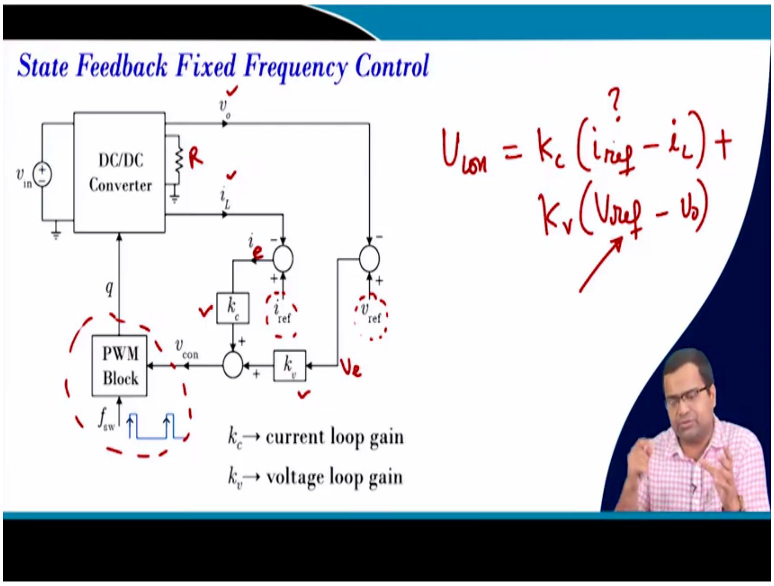

So, state feedback fixed frequency control, if we take a DC-DC converter and here we are considering a resistive load in this converter if we consider this is my error current; if we consider inductor current. Because in current mode control we also sense inductor current and like if it, if you are talking about a buck or a boost converter there are two state variable because we have one inductor, one capacitor.

And generally, we take the current through the inductor as a one state variable and the voltage across capacitor we take another state variable. In this case, since you know we are taking output voltage, which is more or less same as the capacitor voltage, ok.

If there is no ESR then both are identical, but in presence of ESR they are very close to each other. So, if we consider output voltage feedback and then, in a switching converter, we generally design for regulatory purpose. So, output voltage regulation is one of the objective.

So, we need to regulate the output voltage at v ref which is a desired reference voltage and we also you know in state feedback control, we also stay take inductor current as one of the state which we measure using a current sensor and this inductor current can be compared with the reference current.

And then the error current, this is the error voltage error current and error current voltage they are multiplied by their respective gains. For in case of current feedback error we multiply with the current loop gain and for a voltage feedback, we multiply with a voltage feedback gain.

Then the total sum of this is the control voltage or equivalent control voltage and which actually goes into a pulse width modulation block and the job of this PWM block is to generate a gate signal q using the control voltage ok.

And we have discussed this PWM block in case of trailing edge modulation. We generally consider the control voltage with a sawtooth waveform. And then output of the comparator we use output of the comparator is connected to a lag circuit and that lag circuit output is used as a gate signal, that we have discussed earlier.

So, in this control you know current mode control what is the structure of the PWM block for state feedback control as well as I will talk about the current mode control that I will discuss using a MATLAB Simulink model. So, here k c is the current loop gain and k v is the voltage loop gain that we have discussed. That means our control voltage it comprise k c into i ref minus i L plus k v into v ref minus v 0.

While this is known because this is the reference voltage which is given by the designer that we need to regulate at this voltage, but this is something that you have to find out, what is i ref, who gives us i ref? Is it really i ref is given by someone else or we need to derive i ref from some other variables that we will see?

But in case of LED driving application when we want to regulate the current through a LED string, sometime the use of this two architecture, both current and voltage mode configuration can help to significantly cut down the flickering current.

So, I am not going to that, but sometime this structure can be used where the i ref can be available because in case of LED driving i ref is nothing but the nominal current of the LED string and where v ref can be used as the nominal voltage of that voltage across the LED string.

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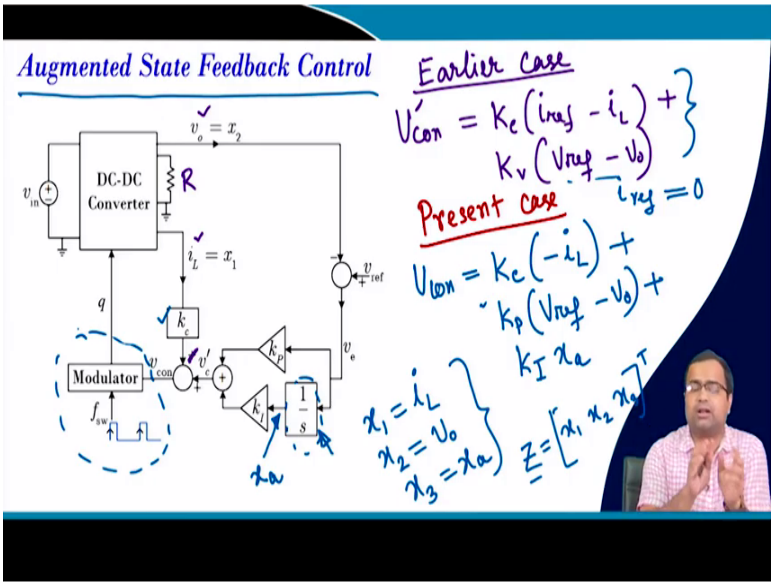

So, now we are going to augment state feedback control. What is this? So, in our earlier; in our earlier study that resistive load. So, this should be a negative sign. In our earlier study what we consider resistive load where we took inductor current as a state variable, output voltage as state variable and which is here, but there are some changes.

So, if we consider our earlier case, our case our V con was V con I can say dash which was our earlier v con, was simply current loop gain there was a reference current minus inductor current plus we took a voltage loop gain where we consider v ref minus v 0. So, this was our idea.

But in the present case; in our present case, if you look at this structure, what is there? In our present case V con we are taking same current loop gain which is here into minus L; that means, we have drop i ref is set to 0 here in this case then next, plus k v here it is k P. So, earlier it was k v that means, there is a gain k P which is v ref minus v 0. So, this is the same thing only instead of k v we are writing k P, that they remain same.

But now there is a third variable because there is an integrator right, and we can assign these states to be an augmented state. Why do we need an integrator? Because in earlier case, if you look at the earlier case if we want to track a step reference in the output voltage, step change in the output voltage, we cannot ensure 0 steady state error because there is no integral action.

Now, in order to track the output voltage accurately, we need to introduce an integral action and that is basically introduced after the error voltage. Once you introduce an integral action, then this increases the order of the system, because one integrator increases one order by one.

And the output of the integrator impact, you know if we recall our initial model development 1 by S term was added in order to realize the dynamics of the inductor current as well as another 1 by S term was used in order to realize the capacitor dynamics.

Because there was one inductance and one capacitance, which have dynamics. Similarly, 1 by S will also have dynamics and output is x a. So, that means, we have a third variable which is k I into x a, that means, now in this configuration our x 1 is I L, x 2 is v 0 and x 3 is our augmented state. That means, now if I combine together I will take a vector which is nothing, but x 1, x 2, x 3 transpose.

So, this is the state vector, the new state vector and we can write down all the states space equation in terms of x 1, x 2, x 3 and the other input variable ok. So, this configuration is called augmented state feedback control where we can incorporate the integral action and we can achieve 0 steady state error in the output voltage. And the remaining structure is same, there is a modulator which converts this control voltage into a gate signal and which is actually going to control the DC-DC converter.

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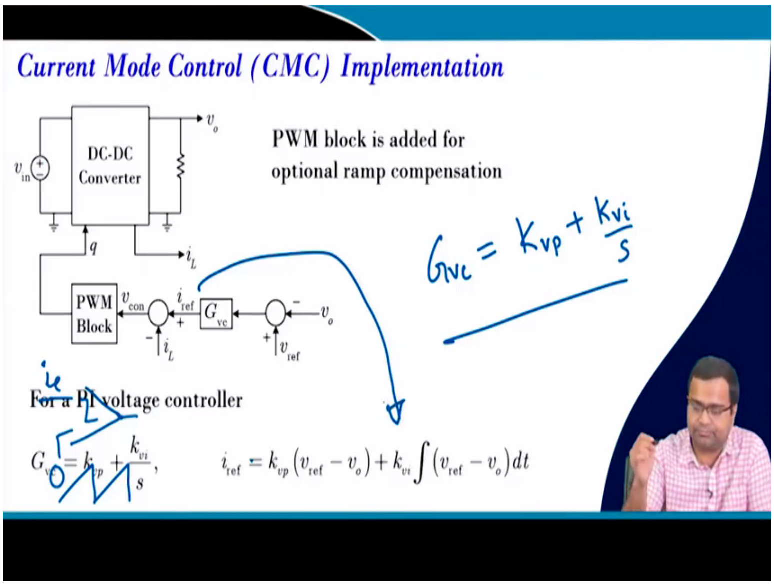

Now, in current mode control, if you look, you know if because we know the current mode control implementation. There is one loop, which is an inner current loop, and there is another loop, which is the output voltage loop; this is the output voltage loop.

That means, output voltage is compared with a reference voltage and this gives us the error voltage and then error voltage; actually error voltage is the input to a voltage controller of the current loop, voltage loop voltage controller.

Then the control output generates a reference current and which is compared with the inductor current and then this will be error current, this error current actually goes inside the PWM block and then it translates this error current into a controllable gate signal. If you do not consider any RAM signal, then this error current is directly compared. This error current is directly compared with 0.

But, if we consider a compensating RAM then this is replaced by, this 0 is replaced by ours sawtooth waveform sorry, it is replaced by our sawtooth waveform like this ok. So, 0 is replaced by the sawtooth waveform and this is a comparator here. So, this is a comparator here and then it has output of the comparator goes to the latch and that will see in the MATLAB simulation.

So; that means, for a PI voltage controller is used for current mode control, it is well known.

And what is the structure of this voltage controller? That means, PI voltage controller is used for a current mode control where our voltage controller is k voltage controller gain plus voltage controller integral gain by S. So, this is a PI controller sometime we use also type two compensator ok. So, this is a structure of the i ref can be represented by in this form.

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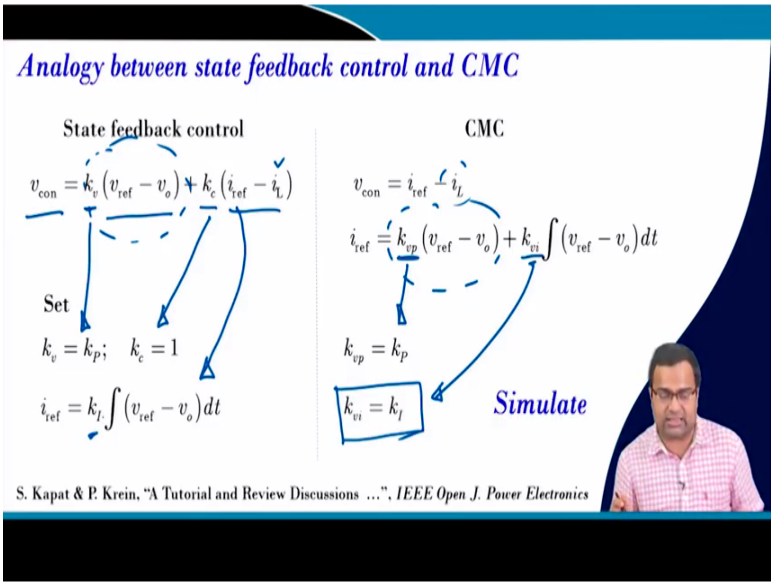

Now, we want to make an analogy. Can we frame this current mode control into a state feedback control? Because in current mode control we also sense both inductor current and output voltage, which are considered being the state of the system, in state feedback control also will sense inductor current and output voltage.

So, whether they are same or they are different, or can we frame one into the other form or not? That is what we are going to discuss. In state feedback control, we saw the control voltage can be represented by the voltage gain into error voltage and current gain into error current.

In current mode control our control voltage is simply reference current minus inductor current, where reference current was generated from a current voltage controller which is a PI controller with the proportional gain of k vp and k vi, that means voltage controller proportional gain and voltage controller integral gain.

And we have shown in this paper, if we set the k v, that means, the voltage controller gain, if we suppose if we set two proportional gain here and current controller gain we set to 1 and then i ref in this case if you set to integral into this controller. Then if I make, if we take the right side if we consider this k vp to be proportional gain, that means, this term and this term they are matching exactly, next i L is already there.

So, it is already there because we took k c equal to 1, next k vi. So, k vi is set to k I because this is the integral gain which is used here, then both will look identical. That means, it is just by taking the right variable and mapping between them. Now, the question is why do we need to do that?

Because we want to using augmented state feedback form, although it is a current mode control, I want to show in subsequent lecture that this will give us an additional degree of freedom. And because in current mode control we generally use an approximate first-order model for the design and in which we lose, we assume that inductor current dynamics is much faster and we just play with the capacitor voltage dynamics.

But in state feedback representation, we have both the dynamics. So, we can better play and we can better separate the loop and particularly when there is a loop interaction current mode control is c the state feedback control can significantly you know, it is very helpful to solve this loop interaction problem, that is another thing.

Another aspect we will see in a subsequent lecture for a non-minimum phase converter the bandwidth, closed-loop bandwidth using traditional current mode control is limited due to the trade up between phase margin and that bandwidth because we need to also achieve a desired some particular phase margin.

That means, around 40, 50 to 60 dB phase margin; degree phase margin. But due to the right of plane 0 that put a limit on the bandwidth, but if you use a state feedback control, we can better you know trade up achieve a higher bandwidth compared to output feedback approach. That will see. But in this discussion, we want to create a simulation case study, let us go back to the simulation model.

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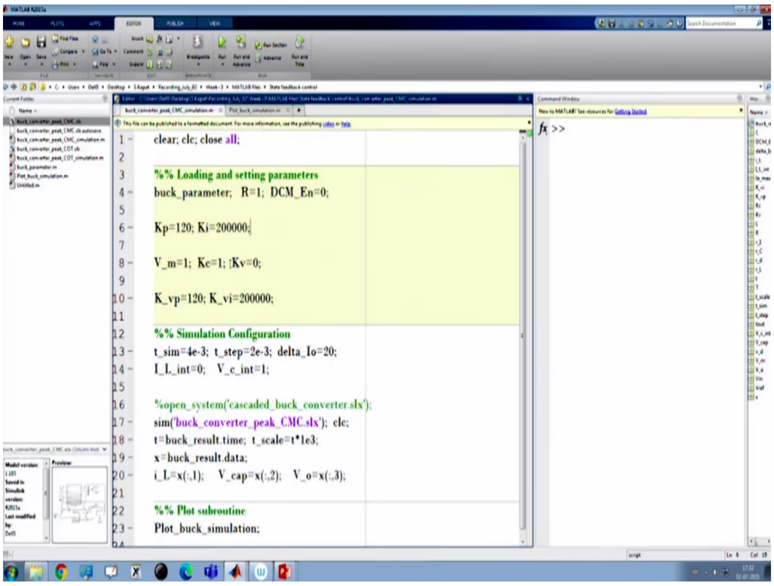

Here, we are showing a peak current mode control and this model is here.

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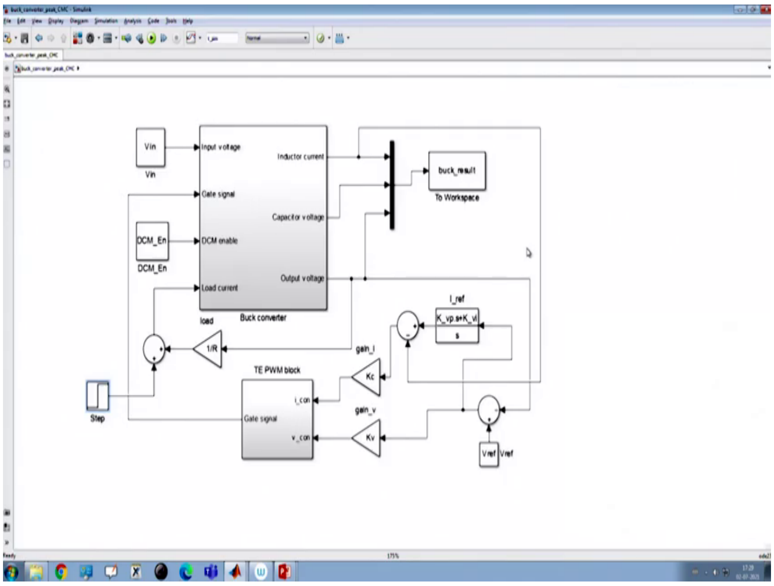

We have discussed enough about this current mode control and this is our standard buck converter, which is already discussed.

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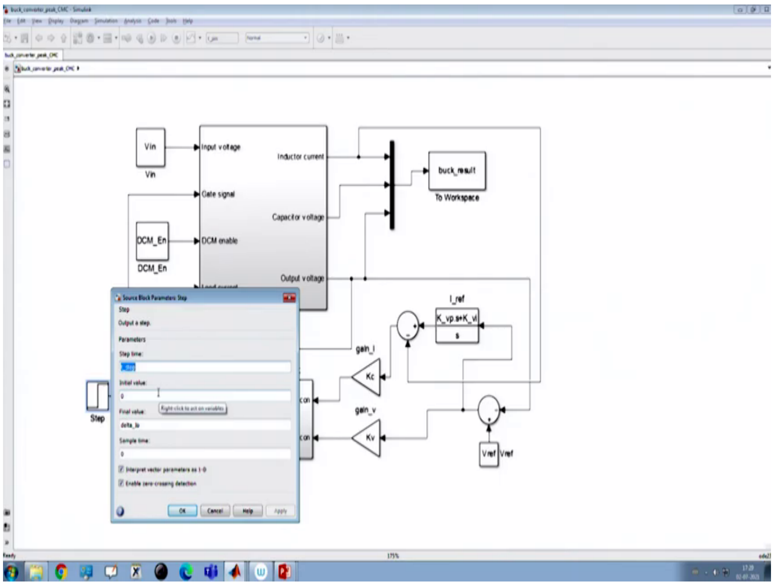

And here we are making a load transient and we have discussed in the previous lecture, the lecture number 16 that we can create the step transient cases in order to simulate ok. And delta i 0, that means, we are using a resistive load and after a certain transient time we want to introduce a step load transient which is a constant current load with a value of delta i 0 and that will appear after t step time. That means we will not put at the beginning. After sometime, we want to introduce a step load transient in the current.

And in the closed loop, I want to show this is a modulator block. If you recall, in our configuration of state feedback control we have used the current loop gain into current error. We have used voltage loop gain into voltage error.

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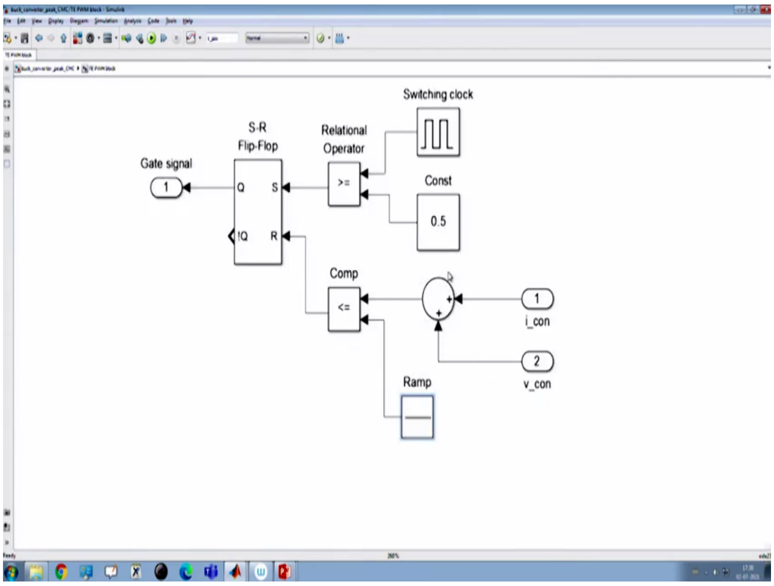

And then we have added them together, added them together and then it is compared. Now, if we set the reference RAM to be 0 then it is the case of current mode control I will show where there is no compensating RAM. If we add some small amount of RAM then that RAM this summation of these two control current and control voltage addition they will actually get compared with the RAM signal.

So, this block is basically or PWM block ok. Next, if I want to realize state feedback control, we have to set K c and K v. I have told you that in current mode control, we use a PI control as the voltage loop because this is the error voltage. This is the output voltage, this is the reference voltage, and this is the error voltage. We take the error voltage as the input to the PI controller and the output of the error voltage is the i ref we call it as a i ref, maybe this is a reference current ok.

So, this is our reference current and this reference current is compared with the inductor current. This is my inductor current and then the inductor current and reference current that generate the error current and we multiply with K c. Now, in state feedback implementation, what we want to do? We can simply keep all the controllers to be 0 and it is simply to compare, but we need to set some reference current.

So, what should be the reference current? And I told you in current mode control we will keep the current loop gain to be 1, voltage loop gain to be K p and for the PI controller the voltage loop proportional gain will be set to 0 because already that is taken care here and current loop K vi integral gain is set to k i ok.

So, let us go back and check the same parameter. So, initially I am taking a very small RAM 1, my K c is 1 K vi can set to K p. That means, I want to set a proportional gain. Let us first fix or proportional gain my K p equal to let us say 120, my K i equal to something like this ok.

So, in current mode control we take this to be K v equal to 0, we can simply take a PI controller form there or we can take, if we go back we can take this to be our proportional control because it is error voltage ok. So, that means, our K v equal to K p.

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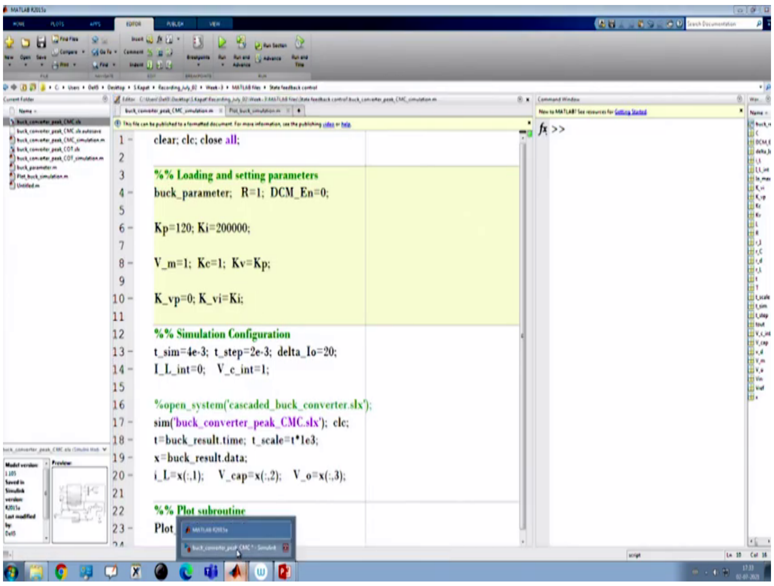

And this K vp equal to 0 and voltage error is simply K i. So, this is our standard current mode control in which we are taking this architecture ok, hold on. That means, in case of yeah this is a current mode control K c is set to 1, this is set to 1 for both the cases and if we consider a standard current mode control, then our inductor current is directly compared to the reference current. So, we do not need additional voltage loop because that is already taken care here.

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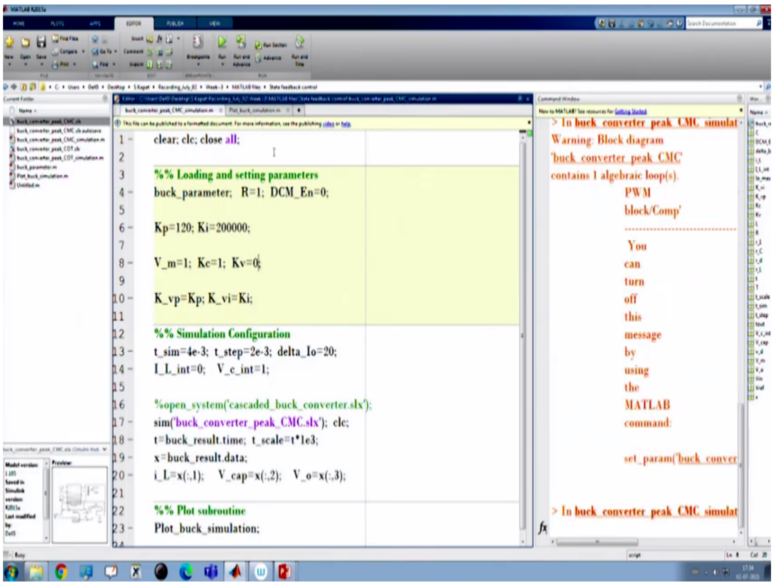

So, in case of current mode control we will simply set this K vp equal to K p because it is the outer loop voltage loop K i and this K v equal to 0, this is our current mode control structure and we want to show the result. So, this is our current mode control result.

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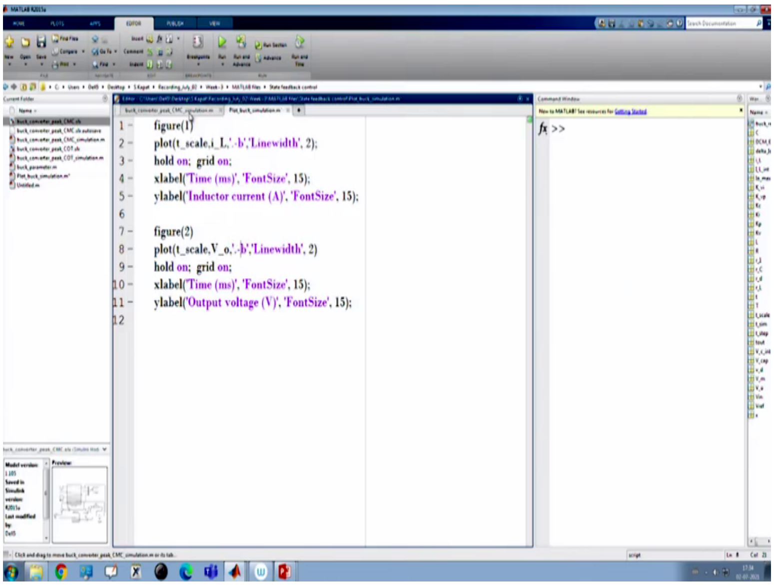

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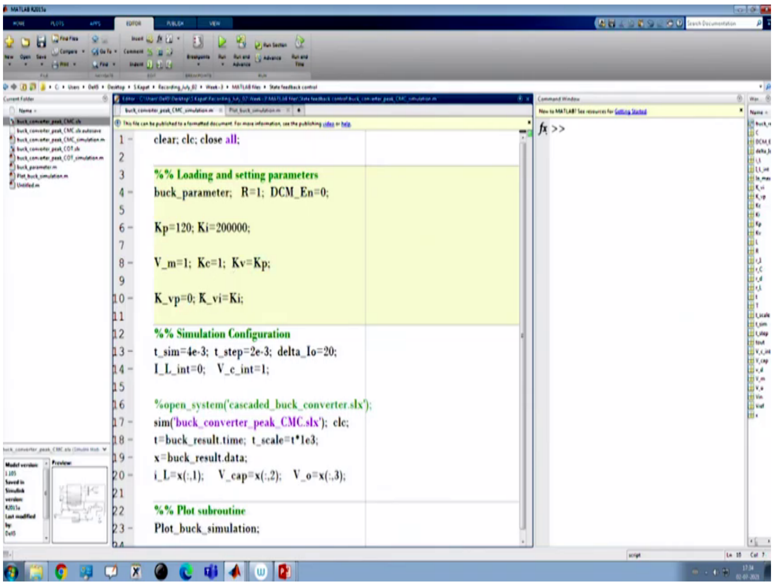

Now, we want to compare this result with our, the same state feedback approach that we discuss, where we will take K v to be K p, this to be 0 and because in state feedback control what we discuss, this will generate I ref which is the integral of the error.

And so, we have a current loop gain, that means, error current reference current is generate as an integral of the error, subtracted by the inductor current then into controller gain and the voltage controller gain is set to K p ok. So, voltage controller gain is set to K p and we want to run the simulation again.

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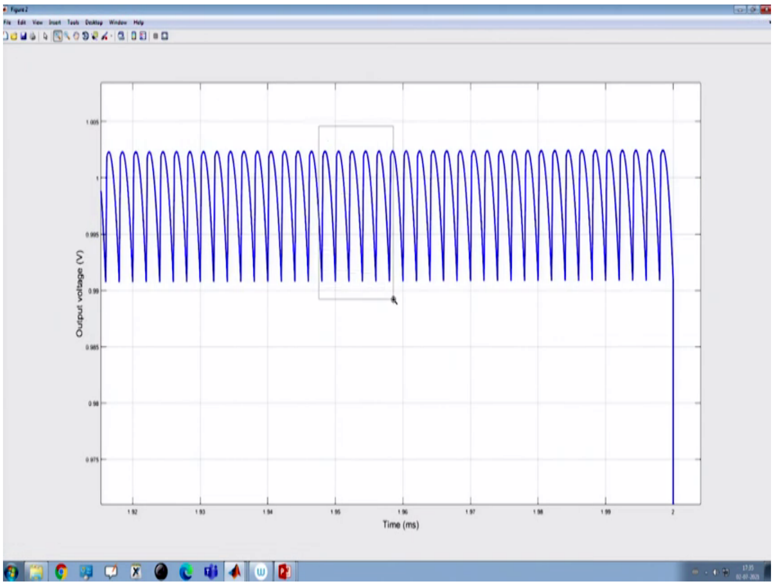

And they are exactly identical because they overlap with each other ok.

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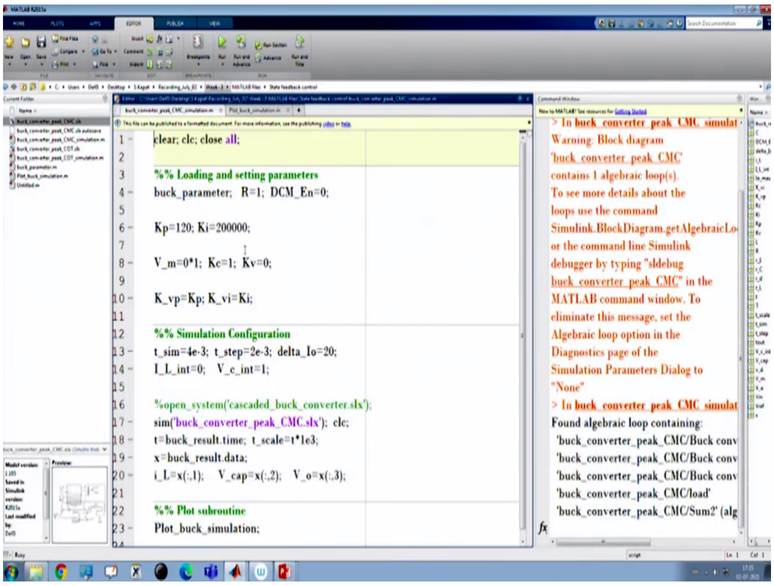

But in current mode control, suppose if we do not incorporate RAM, suppose you set RAM to be 0 and in current mode control we set this to be 1 these to be K p and let us run it for current mode control ok. So, here we are not considering any RAM.

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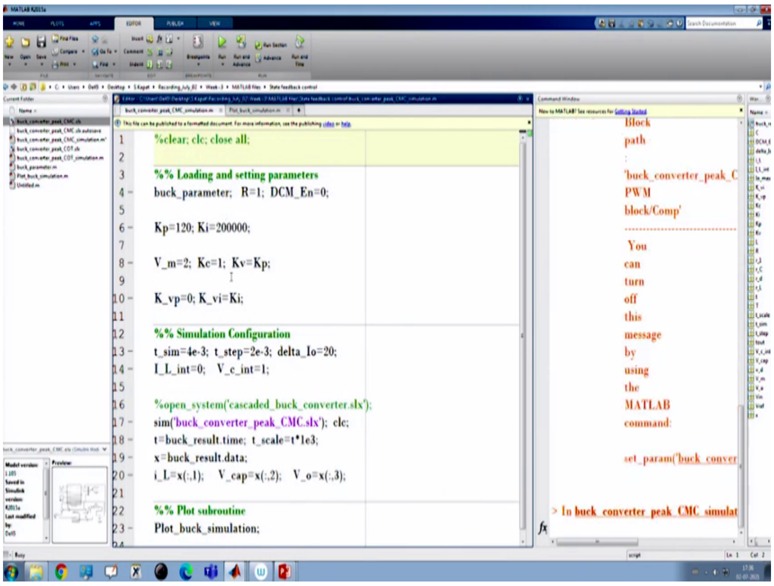

Now, we are putting a RAM (Refer Time: 23:09) of 2 and we are using solid line and here we are setting K p and here we are sitting 0 ok. So, here ok, let us see that what happened that two architecture.

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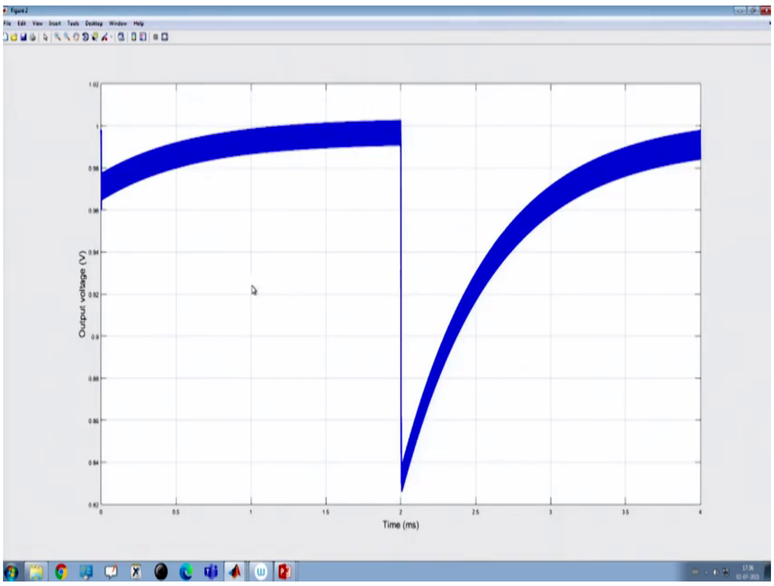

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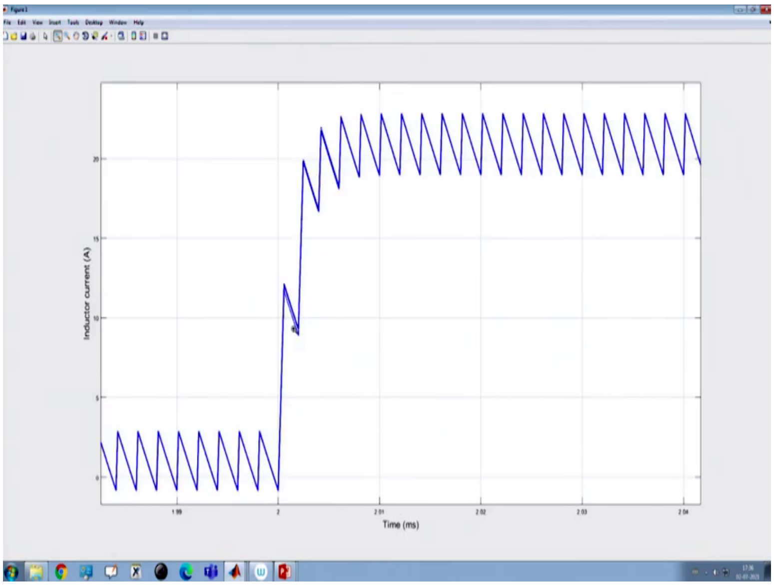

So, if we go through the inductor current waveform there can be slight change, very in significant change, but I will check it, yeah. There is a slight change if you take this dotted curve ok. So, that means, the state feedback control and the current mode control almost resemble each other and in state feedback we have added a compensating RAM, which is a sawtooth waveform, ok.

Whereas, in current mode control, there is no sawtooth waveform they are closely same. The next task is that in state feedback control we can simply set another current reference and we can simulate right. So, that means, we can get an equivalent analog analogous.

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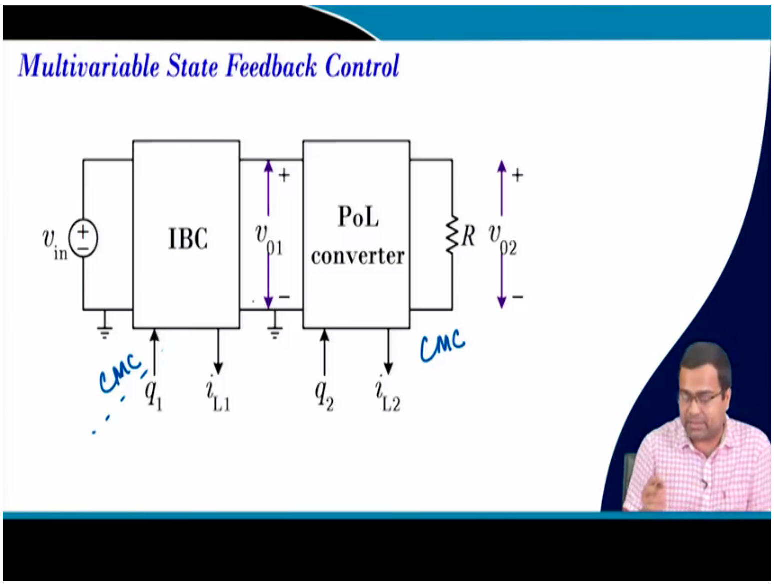

Now, this state feedback approach is very useful, particularly when you are dealing with this intermediate bus architecture in which we consider an intermediate bus converter which is a source side converter and a PoL converter which are load side converter.

And we discuss in lecture number 16 that in order to provide active damping, we consider current mode control for IBC as well as current mode control for PoL converter. So, once we talk about current mode control, that means we can transform this realization into a state feedback form and the same thing is for the PoL converter.

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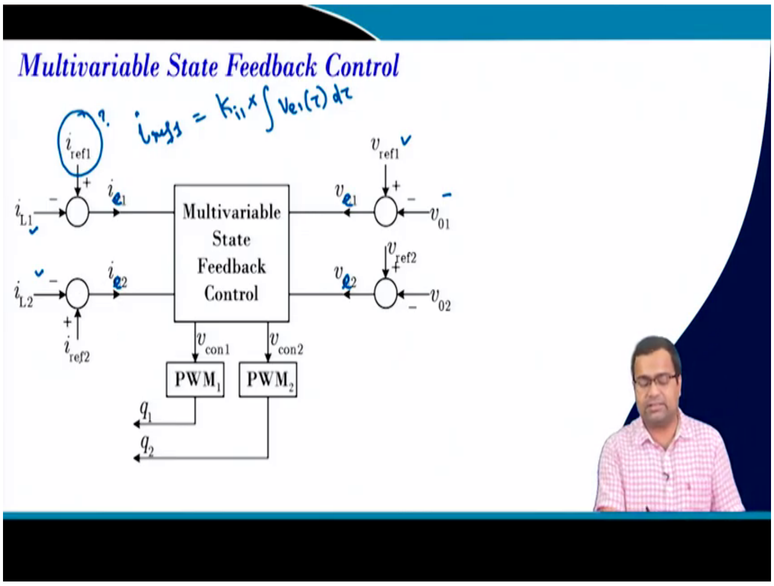

That means in case of current, that means, in state feedback form. We can again generate a reference current for the IBC and this is my error current, this is my error current, this is my error voltage and we can as well. That means, it is compared with my inductor current one and for this reference 2 I can compare with inductor current 2.

And similarly, I can compare with the reference 1 for output voltage 1 of the IBC and v ref 2 is the reference voltage for the PoL converter I can compare with the output voltage of the PoL converter.

So, we will generate the error voltage. Then what we do? How do we generate i ref 1? So, i ref 1 we discuss in current mode control can be generated by the integral action of the error voltage of that particular error voltage.

That means, if we take this error voltage, this can be i ref 1 can be simply some integral 1 into error voltage of ve 1 you know d tau right. Similarly, I can take I can generate i ref 2 by the integral of this error voltage 2 and we can represent into state feedback form.

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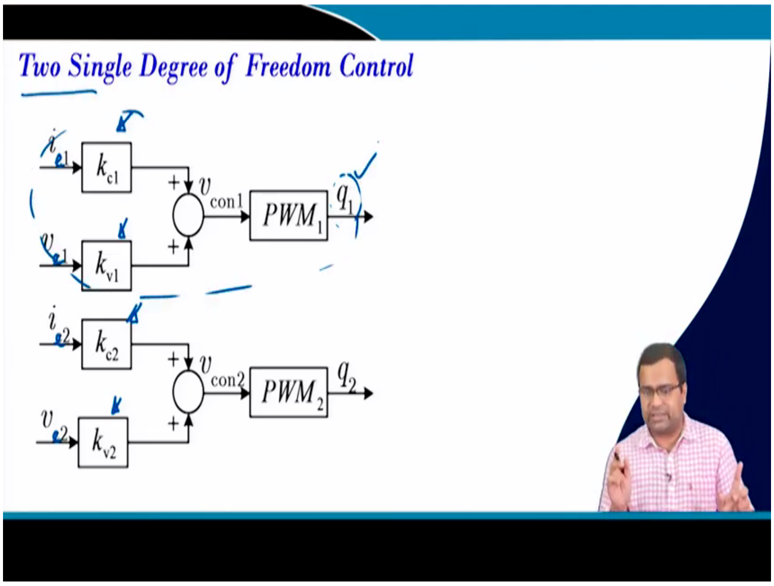

Once you represent into state feedback form. Now, we have a k c 1 which is the current loop gain of the first stage converter. It also has a voltage loop gain, current loop gain of the second stage converter and the current loop gain of the voltage loop gain of the second stage converter, these are all error current, error voltage, error current, error voltage and then we can.

So, this is one way of control in which we are generating the gate signal of the IBC by its own loop, that means its own inductor current feedback and own error voltage feedback. Similarly, we are controlling PoL converter by its own feedback loop ok. So, that is why it is called 2 single degree of freedom, for each case there is a 1 degree of freedom, because only one control variable is q1.

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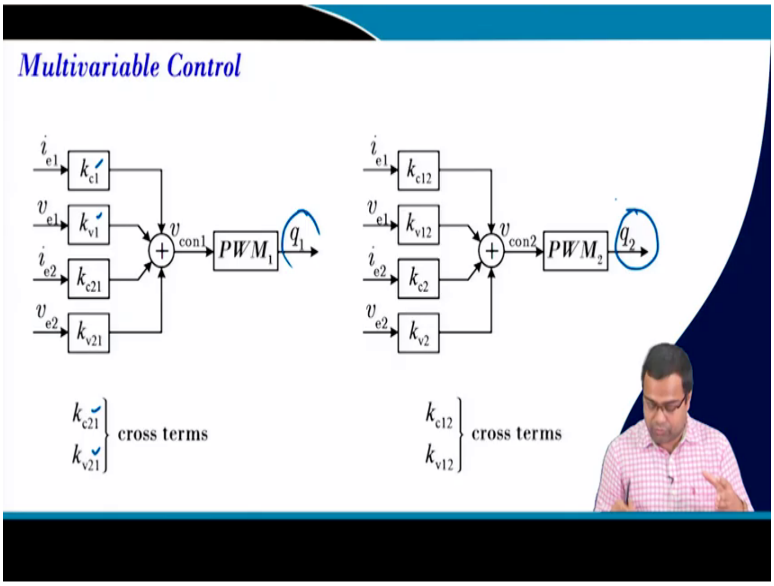

But, since we can represent into a multivariable form we can actually represent this into a standard you know state feedback form, in which it's a multi 2 input, 2 output system there are 2 output, 2 output voltage and 2 input q 1 and q 2. And there will be self term which is like a k c1 and kc k v1 and there will be cross term which will be k c21 k v21.

Because of the first loop, the first converter gate signal can be generated by taking the feedback of its self current and voltage as well as the other converter current and voltage error information. Similarly, the out PoL converter output can be generated by the combination of its own current and voltage as well as the current and voltage error of the IBC.

So, by this multivariable control because whenever we do this single you know 2 degree of freedom, 1 degree-of-freedom control 2 single like a 2 different forms. We do not take into account the coupling effect. This can introduce a coupling effect and we may not be able to handle properly.

But if we represent into this multivariable form, then we can actually take care of this coupling effect by means of state feedback representation and suitably placing the closed-loop pole. So, that we can attempt to decouple the 2 systems. Provided that their time scale separated.

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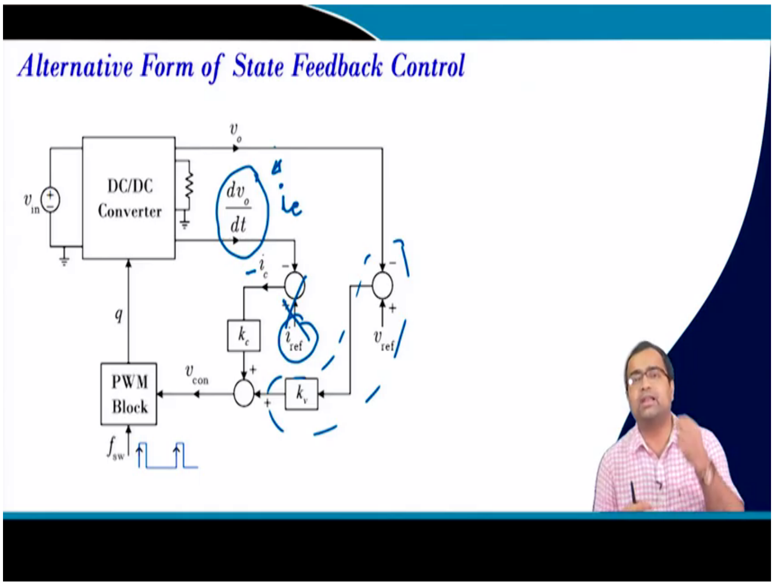

The alternative form of state feedback control, that means, instead of inductor current, we can also use the derivative of the output voltage as you know, derivative of the output voltage to be another state. In this case, we may not need a reference current because for a buck converter the derivative of the output voltage actually carries the information of the capacitor current.

So, which itself average is 0. So, we do not need to take any other reference voltage. So, we can straightaway take this current, that means this is a negative capacitor current and that can be added up. And we are already taking a, that means this part is common, but now instead of earlier inductor current we are simply taking the derivative of the output voltage, which will generate, which will represent the capacitor current.

But it may not be true for a boost converter where the direct derivative of the output voltage is not recommended because the boost converter has discontinuous output voltage ripple and that can induce or inject significant switching noise into the closed loop.

And if we want to, if we put a low-pass filter then we actually you know actually cannot capture the high frequency current information because we are actually putting a low-pass filter. So, it will attenuate the high frequency current information. So, the direct derivative may not be a suitable choice for a boost converter, but it could be a useful for buck converter.

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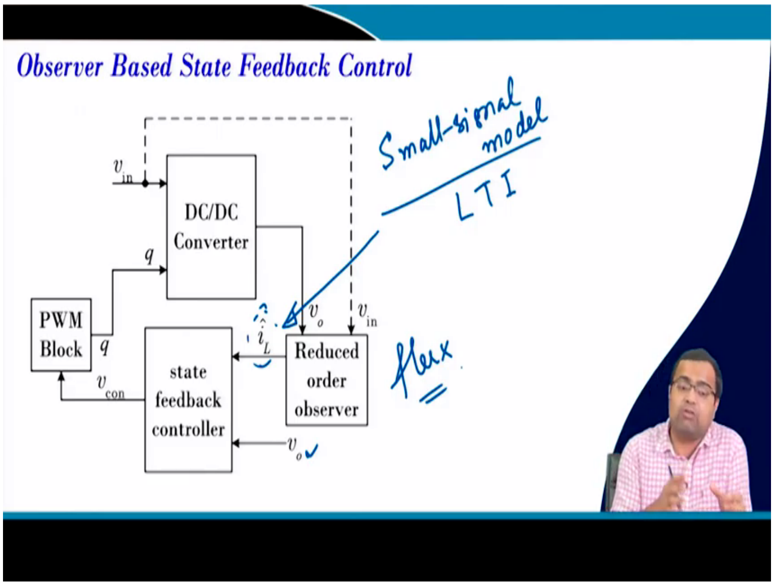

Now, we can design observer based state feedback control in which our in output voltage can be sent directly, but the inductor current can be estimated. So, you can use a reduced order observer. Now there are two ways of designing this observer. Basically, the modelling of this system, the one way we can use a small-signal model ok.

If we use small-signal model, then the whole converter model can be realized into a linear time invariant system form. Whether it is a perturbed dynamics form we can represent and then we can use our traditional reduced observer theory to estimate the inductor current information.

But this technique relies on small signal, depends on the small-signal model and we know that if we want to increase the bandwidth of the system, then there is a model limit on the control. Because the model is may not be valid when the perturbation in the duty ratio is large and that can significantly deviate the actual behavior of the converter. So, this model may not be suitable for designing a high bandwidth observer.

Whereas, if you use a flux based approach, that means, if we take the voltage across the inductor and use a non-linear observer by flux based approach. Then we can actually generate the switching ripple information of the inductor current and by that way we can get a very high frequency current dynamics and we can estimate the current more accurately, including high frequency dynamics.

So, this technique can be used for switching converter, which retains fast dynamics of the current loop. Then we can use, we can take the advantage to realize the current mode control architecture like an advantage of the current mode control feature. But without sensing inductor current because this is a switching converter. So, linear model may not be a good choice.

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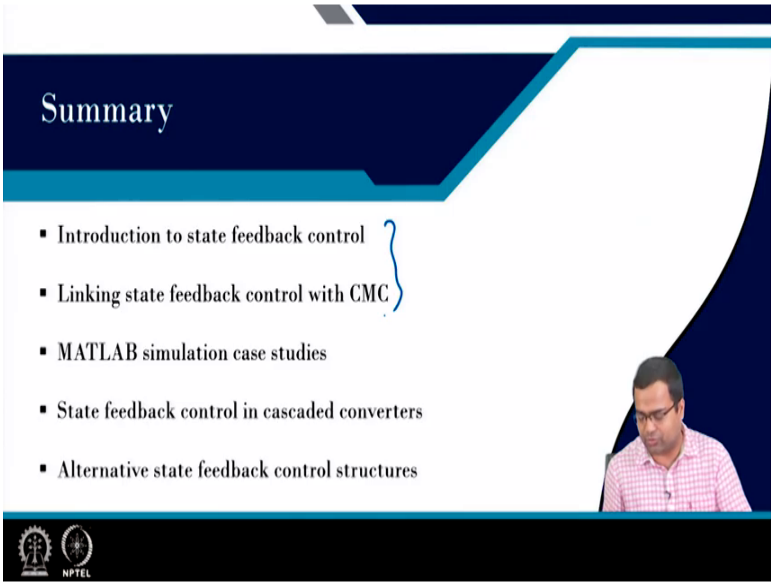

In summary we have introduced state feedback control and I have shown using simulation that link between state feedback control and current mode control using simulation case studies.

And we have also discussed the overview of state feedback control in cascaded converter where instead of designing individual converters standalone configuration we can use a multivariable approach to better you know design a centralized control for better transient performance as well as the decoupling between the two converter by means of a state feedback approach. And then we also discuss some alternative state feedback control structure. So, with this I want to finish today's lecture.

Thank you very much.