Control and Tuning Methods in Switched Mode Power Converters
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Lecture – 15
Single and Multi Loop Feedback Control Methods

This is lecture number 15. In this lecture we are going to discuss Single and Multi Loop Feedback Control Method.

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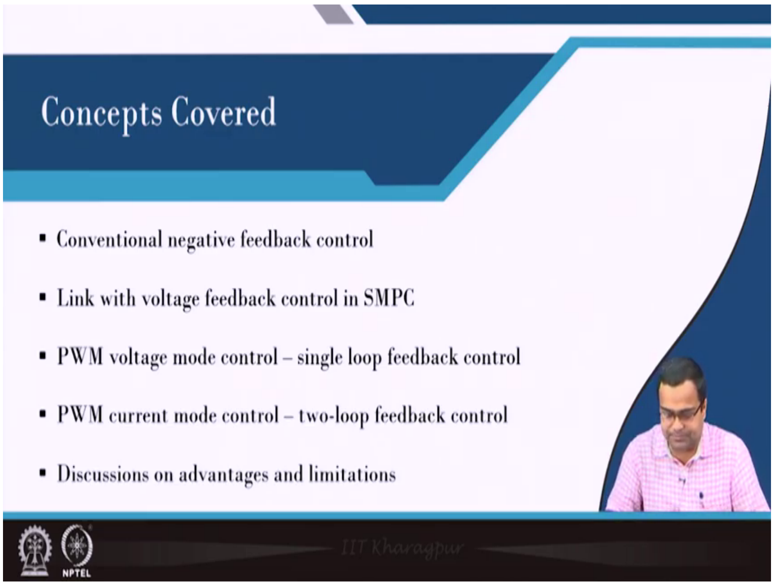

Today, we are going to cover conventional negative feedback control, then link with voltage feedback control in switch mode power converter. Then, PWM voltage mode control, which is a single loop feedback control, a very well known method. Then, we are going to talk about PWM current mode control, which is a 2 loop feedback control.

And finally, I want to discuss some advantage and limitation of this multi loop and single loop feedback control methods.

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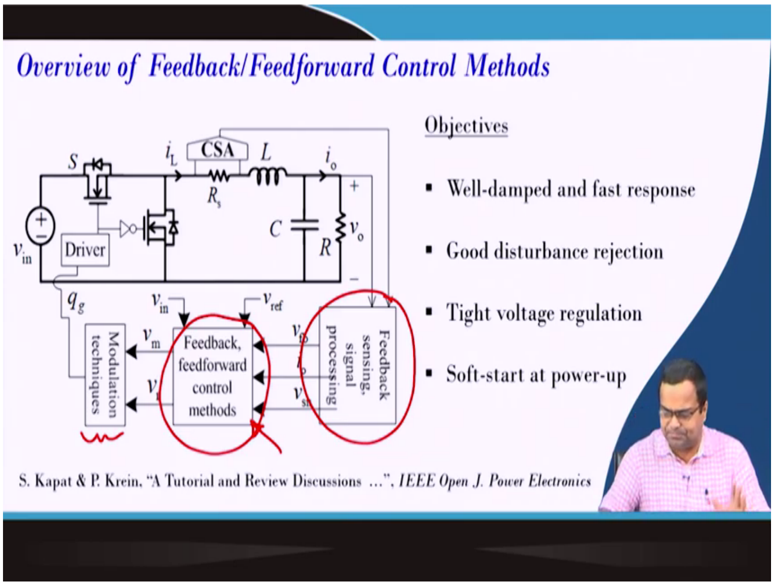

So, first I want to show the overall block diagram of the feedback and feed forward control method. And, we have already discussed that in this method; we need a sensing circuit like a sensor. This includes a feedback sensor like a resistive voltage divider, then we can also consider one unity gain buffer circuit and so on.

And, then the feedback control method, which include error amplifier. Compensator, you know, and also the control logic, what control logic we are going to consider. And, in this lecture, we are going to discuss like; you know the series of lecture, first fixed frequency control then variable frequency control. So, this structure will differ, based on what control logic we are going to discuss.

This next part is a modulation technique and this we have already discussed in week 2 series, where we talk about fixed frequency modulation, variable frequency modulation.

So, even though the feedback control structure may be same, the modulation can be different. And, as a result, you know, the stability and other condition can be different, which we have already discussed. So, now, we want to take one by one different control method. What are the objectives in this control design or in the feedback control? The first our system should be well damped and it should offer fast transient. Second, it should have a good disturbance rejection.

In fact, we saw in the previous class that feed forward control, which can substantially reduce by effect because of the input voltage variation, the effect because of the load current variation. So, this technique can also be incorporated for disturbance rejection, but without feed forward, feedback can also reject disturbance, but I mean it has some limitations, because we also discuss that it takes time to respond to the disturbance.

So, feedback feed forward action can speed up. We also want to achieve tight voltage regulation, and this is where the feedback control plays a significant role. Because, you can have you know parameter uncertainty, we can have a, we can have disturbance, we can have component tolerance like component variation, edging effect, but despite that we need to regulate the output voltage. And, sometimes also output current like, depending upon the application.

And, finally, I will also discuss today's class, today's class that, how if you turn off like power off the power supply or the converter; that means, that is called the start-up process; that means, everything start from 0 the voltage and current starts from 0. So, if you suddenly you know enable the feedback control logic from the very beginning, then what can happen, I mean what could be the overshoot and undershoot of the current and voltage, that also we need to discuss.

And, then we also want to discuss some of the soft start technique, which can smoothly you know transfer the voltage to it is desired value, despite the feedback loop being activated ok.

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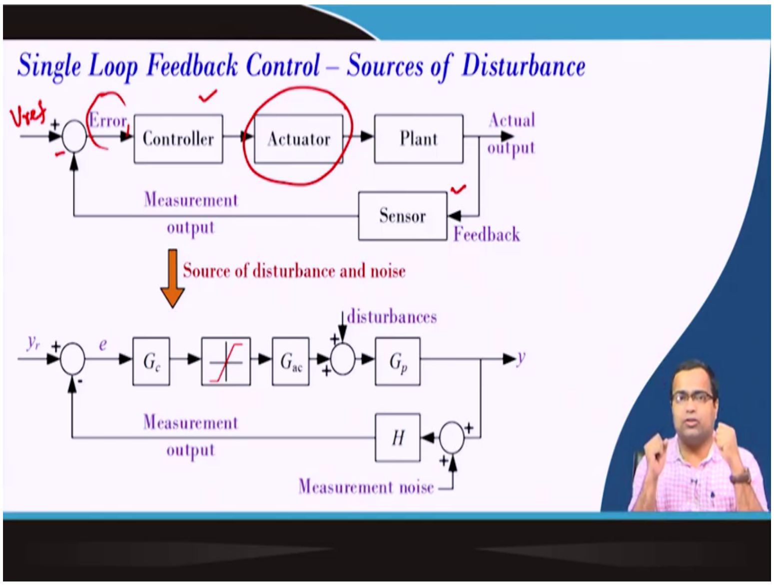

So, in single loop feedback control, if we take a typical, like a traditional control, you know feedback control. So we have a sensor, which sense that what signal you are going to take the feedback. In some cases, in most of the cases in power supply, we need to sense the output voltage, because we want to regulate the voltage.

Then, this goes to there will be a reference signal. So, this reference can be voltage. If it is a voltage regulator, if it is a current regulator, this can be a current reference and we need to sense the current which current we want to control. In some cases, we want to control the inductor current, in some cases we want to control the load current. Then there will be a controller, the error voltage or the error signal the irrespective of whether it is a voltage or current.

Then, the controller whether what type of controller it is? Like a standard controller, we know about proportional, integral, derivative, lag-lead compensator, then this controller output will go to the actuator ok. And, this actuator actually goes to the plant. So, in power converter, we will find these actuators are nothing, but the controller is implemented using op-amps. But, the actuators are typically driver circuit, which try to because whatever gate signal we generate you know in terms of modulator, this includes modulator like a driver, latch.

So, ultimately, that signal should turn on and off a switching circuit; that means it should have sufficient current to turn on the switch within a reasonably small time, you know, that requires a driver circuit. This is because it has to turn on and turn off power mass space, power devices. So, the sources of disturbance we have to discuss in typical control systems, that disturbance can occur. You know after this actuator output, it can also happen like you know part of the process.

And, the noise actually occurs at the measurement point; that means, we are trying to sense the output voltage and this noise can propagate. So, there are you know that noise can happen, this noise can be like you know white Gaussian noise, but despite this noise and disturbance we have to design the controller or the compensator.

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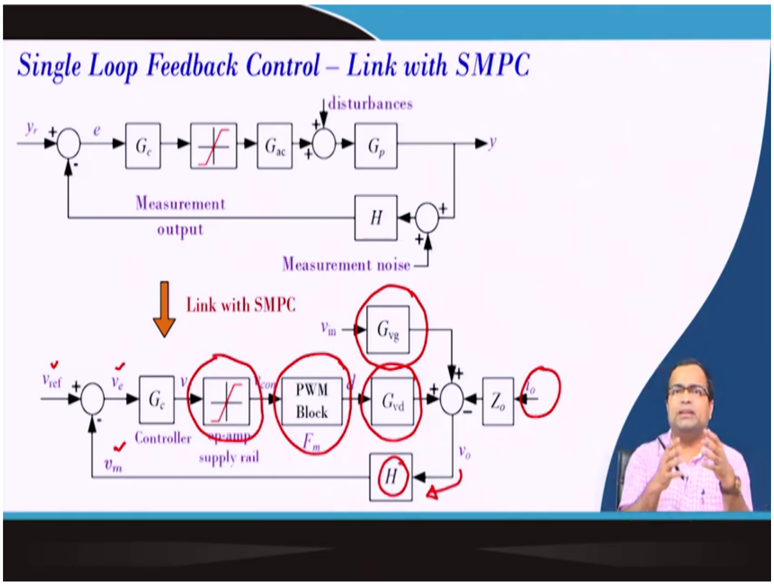

We want to link this single loop, because it has only one feedback loop and whether it is a voltage loop or current loop, that we will discuss, a single feedback loop.

And, if we want to relate this with our switch mode power converter, then if we take a voltage feedback; that means, this is the output voltage coming out of this converter. And, this output voltage is sense and actually this H the feedback gain; this may include the resistive divider ok. So, this is a measured voltage, and this is compared with our reference signal. And, then we generate the error voltage and then we implement a controller.

And, generally an op-amp is used to implement controller, that means depending upon whether we have to implement type 2, type 3, PID p i. So, the number of op-amps will vary in general you know one op-amp may be sufficient, but the op amp has a supply finite supply rail; that means, it has a whether it is a dual supply rail or it is a unipolar op-amp, depending upon that there can be a saturation nonlinearity. That means we cannot increase the grain of the compensator, which can saturate the output of the op-amp.

And, this saturation can cause some non-linear effect, which cannot be captured by a linear analysis ok. Then, control output goes to a feedback controller, feedback modulator block, PW modulator block. In case of fixed frequency, this modulator is a like a fixed switching frequency and it generates the gate signal with a certain duty ratio ok.

And, this duty ratio, if we try to derive the small-signal model, this control to output transfer function is this one, then there can be disturbance in the input voltage, which will be affected, you know and which can affect the output voltage, there can be a disturbance in the load current, which can affect through the output impedance. So, all these actually add up to generate the output voltage.

So, any disturbance, either an input voltage load current or duty ratio, can cause a disturbance in the output voltage and that comes to the feedback loop and then feedback controller takes the action.

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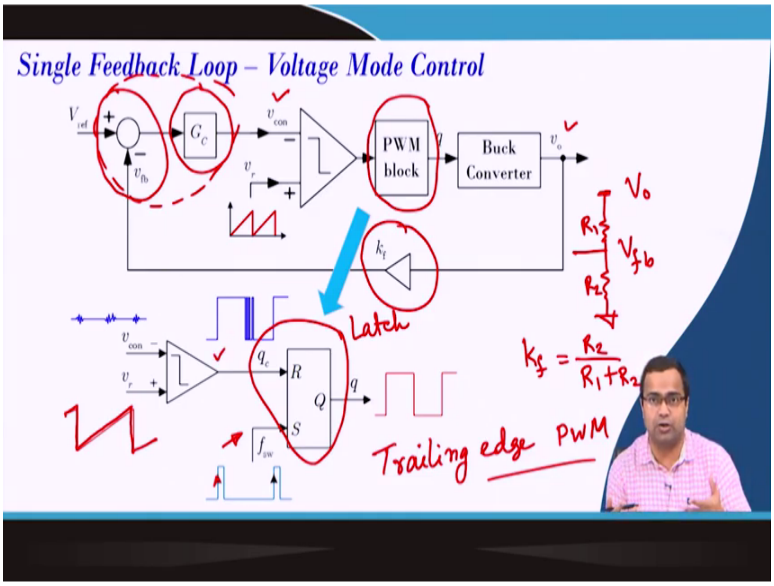

So, in case of voltage mode control, the output feedback as we discuss it is a voltage, this is the output voltage, and this could be a resistive divider.

That means, you know, we can simply consider a resistive divider path; that means, this can be the actual output voltage and we can tap this; this is my feedback voltage ok. This is my actual voltage and we can put a R, R 1, R 2 and this k f which is the feedback gain is simply R 2 by R 1 plus R 2 ok. But we need to take care, we need to you know consider the loading effect. So; that means, this resistance value should be much higher than the load resistance of the buck converter DC-DC converter.

And also, we need to you know in many cases; we need to match the impedance. So, you can put a unit gain buffer for the impedance matching. And, then we take the feedback voltage and this is where the error amplifier comes. In fact, the compensator in integrated circuit or even op-amp, even the whole thing can be implemented using a single op-amp, ok. Or you know for sake of simplicity you can use multiple op-amp, one for error amplifier and few more for let say PID controller.

But practical circuit like a type 2, type 3 compensator one op-amp should be sufficient and then it goes to the comparator and there is a sawtooth waveform. Now, this PWM block, which in fixed frequency, it is we have already discussed. If we take a trailing edge modulation, what we found in the trailing edge modulation, we have a sawtooth waveform right, this is my sawtooth waveform. And, this control voltage, which is the output of the controller, is compared with the sawtooth voltage.

And, then the comparator output is passed through a latch circuit. So, this is my latch circuit, this is my latch circuit. And, this latch circuit is a sink with the external switching clock and this generates the gate signal for the converter ok.

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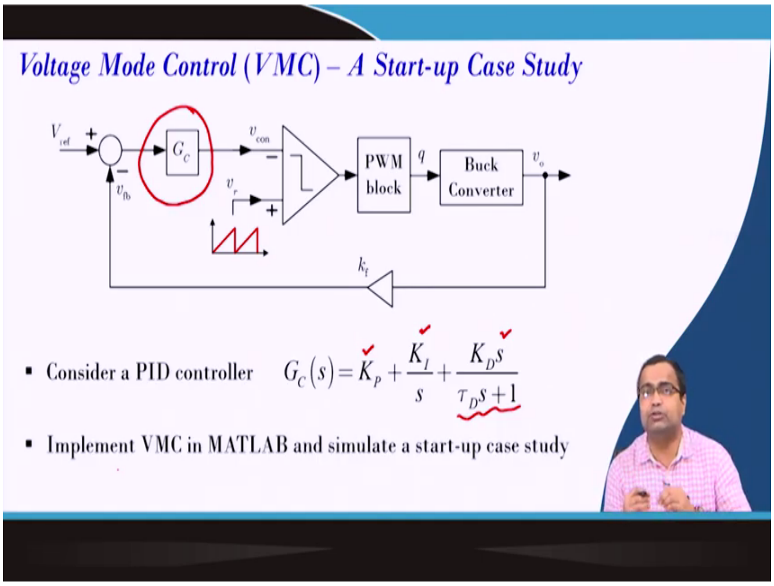

So, I want to consider a start-up case study; that means, we have discussed already this trailing edge modulation. This is like a trailing edge modulation, this is a trailing edge modulation, trailing edge modulation, we have our trailing edge PWM.

Because, the switch turns on at every rising of the switching clock that we have discussed. And, switch turns of based on the comparator condition, this comparator condition ok. So, this condition actually decide when the switch should be turned off. Now, in voltage mod control I want to show a start-up case study ok.

So, for the time being, let us consider a PID controller. In fact, I can tell you that a voltage mode control. Typically, people either use a PID controller or a type 3 compensator is which is like a lag-lead compensator. And, that we will take separately in the design of PID controller in the subsequent lecture. But, today I want to consider a PID controller. The structure of a practical PID controlled looks like this, a proportional gain integral and the derivative.

So we cannot implement an ideal derivative, because we have a finite bandwidth limit of the op-amp. And, also we do not want to inject high frequency noise. So, we put a low-pass filter, but this time constant should be sufficiently small. So, that we can retain the useful information at the same time we have to attenuate the noise.

So, we want to implement the voltage mode control in MATLAB and we want to simulate a start-up case study ok.

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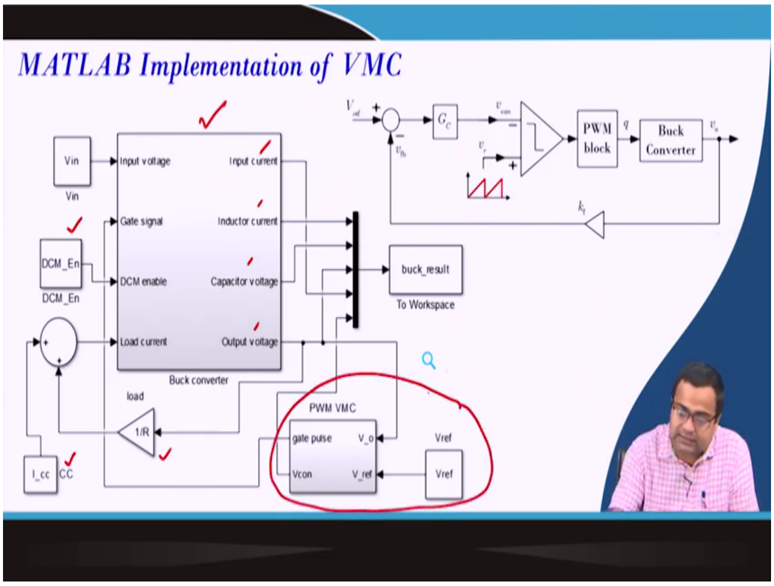

So, I think we have to move before going to the MATLAB implementation; I want to show the MATLAB diagram. So, this is the converter diagram that we have already shown. This converter was build up in the very beginning like in the fast week and in the second week, I have shown you that custom block to come up with this system or subsystem for the power stage buck converter, which include the parasitic of the switch parasitic of the inductor, capacitor and switching signal.

Now, we can take everything like input current inductor, current capacitor, voltage output voltage. Everything you can see. So, this model I am using and this the same enable is used, whether you want a conventional buck convertor or a synchronous buck converter ok. And, here we can add an additionally constant current load, separately along with a resistive load ok.

So, in this block we are adding a new one feedback block, which is like this is my PWM voltage mode control block. What is this?

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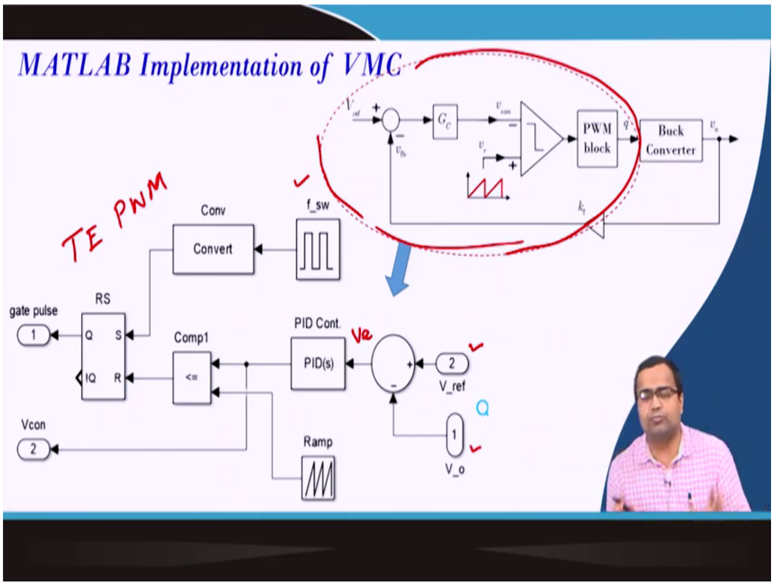

So, if we take this; that means, this whole block is shown here. I mean, if you see this circuit, it is shown here this particular circuit. First of all, we need a switching clock to turn on the switch, because we are talking about a trailing edge PWM, we are talking about trailing edge PWM.

And, this is my reference voltage and the output voltage and this is my error voltage. And, I took here a standard PID controller like a by default PID controller, I can separately implement this PID controller using a transfer function block from the MATLAB.

I will show, already I have shown in the previous class and this is a ramp and the ramp I have chosen that ramp base value and the upper value I can customize. And, this is compared and the comparator output is used to reset the pulse; that means, the turn off the switch ok.

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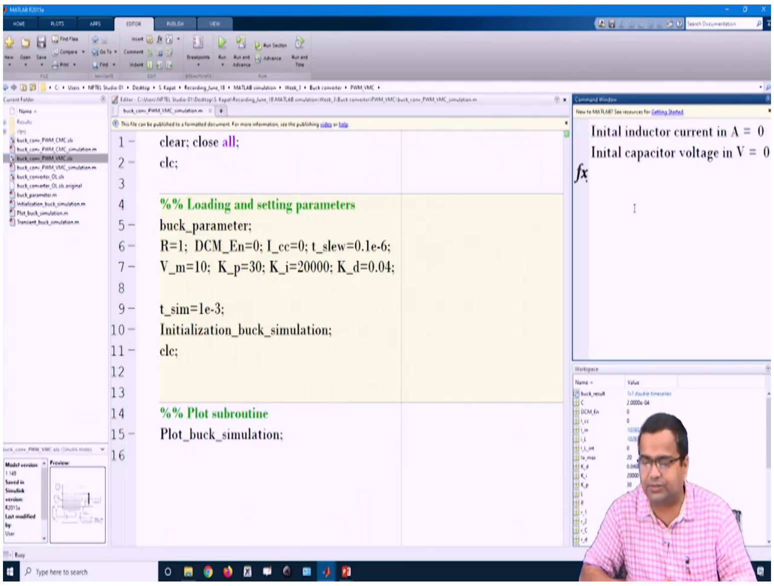

So, let us go to the MATLAB block and see that example ok. So, in this example, we are going to consider PWM voltage mode control, that we have I have shown you.

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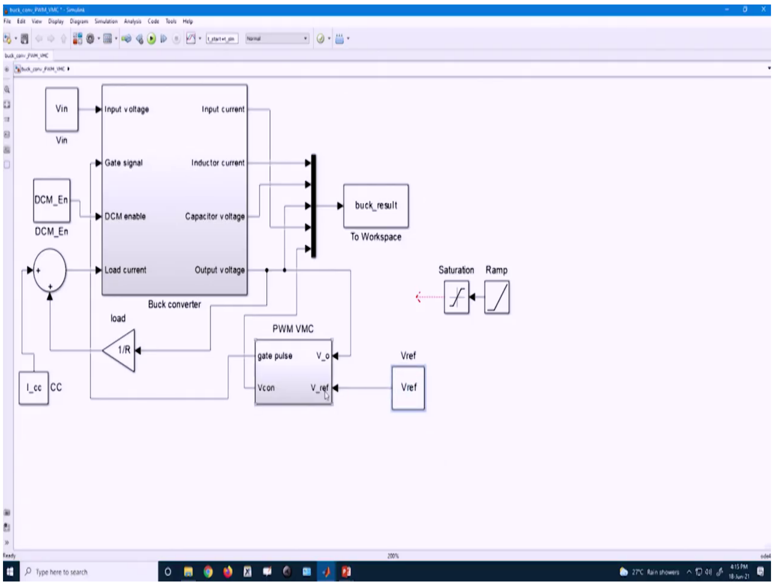

So, in this diagram initially I want to show that this block I will discuss, what is this? So, for the time being I will just keep this block separately ok, because this block will be use in the subsequent slide it has certain purpose ok, just one ok. So, I am using these blocks separately, but now I want to use a separate reference signal and this is my V ref V ref and this is my V ref; that means, this is my reference voltage ok. So, the reference voltage is coming and this block I have already shown the feedback block.

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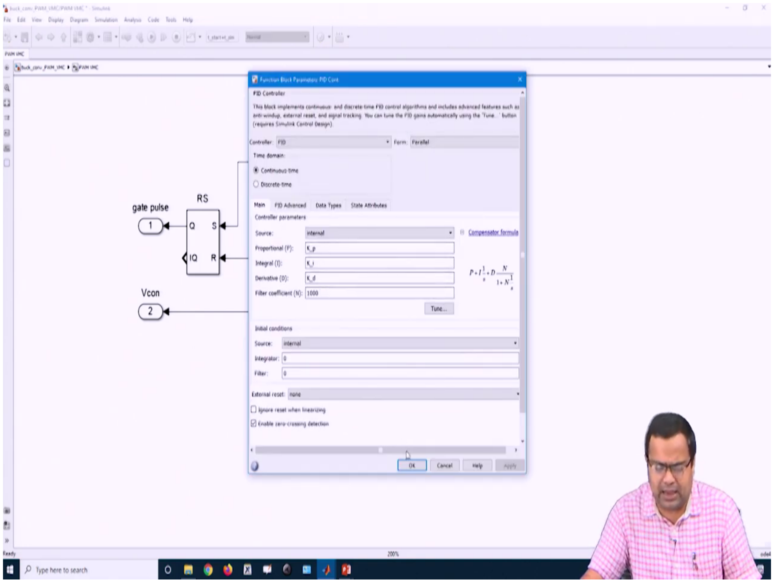

And, the gain of the controller are here assigned like K_p K_i K_d and which I am calling from the external MATLAB file ok.

So, this is like a standard voltage mode control that I am going to discuss ok. I said some value K_p K_i K_d and the upper limit of the sawtooth waveform is 10.

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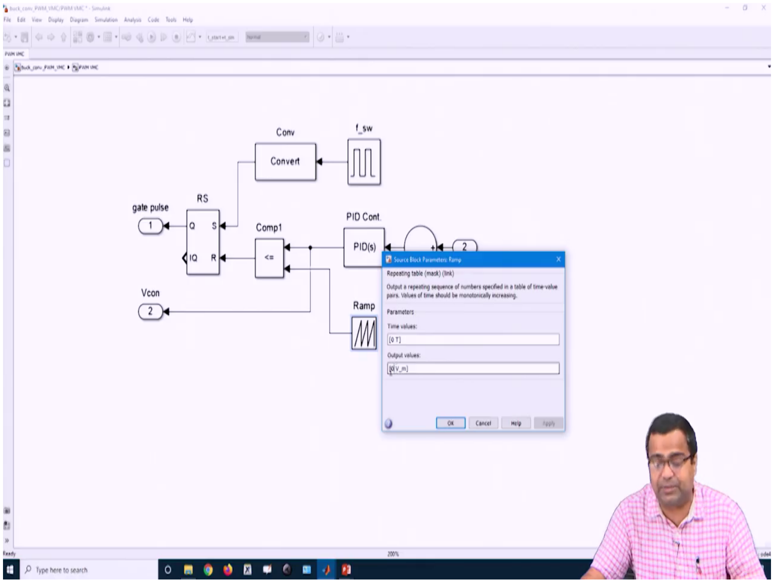

That means, if I go here this sawtooth waveform I set from 0 to V m; that means, the base value is 0 and the upper value is V max V m. And, it is time is 0 to t time period ok. Now, with this let us simulate what I am trying to do? I am trying to I have enable this PID controller from the very beginning; that means, K p 30 K i 20,000 and K d 0.04.

And, I am now running from the start-up from the beginning; that means, it will ask for the initial condition, let me start with the 0 initial condition and we will run it.

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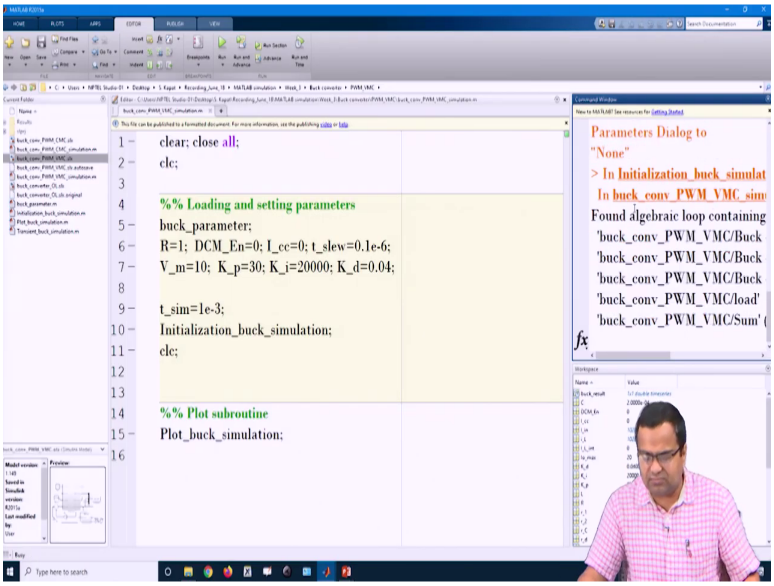

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So, if we run I want to show you that. So, this shows the start-up action, because this particular the top one is my inductor current, this is my inductor current, and this is my output voltage.

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. So, you see the inductor current, actually goes up to more than like close to 80 Ampere just because we are using a gain, maybe it is a large gain.

And, the voltage is also going above 3 volt, close to 3.5, before it is coming to steady state which is 1 4. That means, such kind of huge current it will simply you know it will burn the device or it will damage the switches and the other you know, because our ratings of the components are not designed ok. So, this is not desirable. In fact, the output voltage is too high, because this output voltage we want to regulate and if the overshoot is too high, it can damage the application, because where we are using this regulated power supply.

So, this is where actually I am showing this start-up transient scenario, in this presentation. That means trailing edge modulation. I am simulating this start-up transient and this is what I have shown now.

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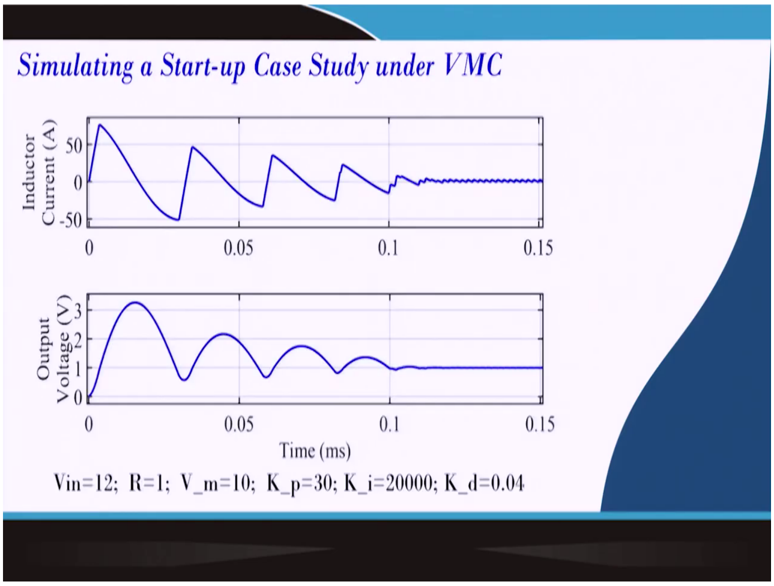

So, here using K p K i K d and you can see the huge transient. Now, the next question how can I reduce this transient effect; that means, how can I. So, I want to so, before I move to shape this start-up action we should also know what are the function of K P K I K D?

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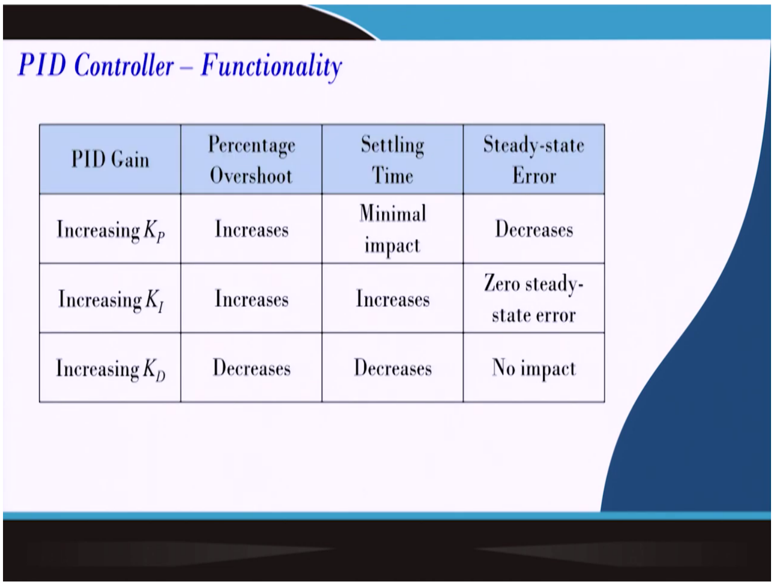

PID Gain	Percentage Overshoot	Settling Time	Steady-state Error
Increasing K_P	Increases	Minimal impact	Decreases
Increasing K_I	Increases	Increases	Zero steady-state error
Increasing K_D	Decreases	Decreases	No impact

Because we have used a PID controller, though we can change the gain, but you know generally I am talking about the analog controller, where the PID controller are set through external component. That means they are set on the at the very beginning of the converter. So, you have probably no choice or very hardly any choice to change this PID controller at the beginning, but we should know that the effect of K P K I and K D. If, we increase a proportional gain generally the percentage overshoot increases or it is vice versa if you reduce it will get reduced.

The settling time it has a minimum impact, but yes, of course, it has an impact on the rise time higher K P will reduce the rise time, but the at the same time it will increase the overshoot. The steady state error can be decreased, the integral action is used to reduce this steady state error and you can eventually go to 0 steady state error, where limit is tend to infinity. But, we set criteria like a 2 percent, 5 percent error criteria, to decide the settling time ok. Then, if we increase K I then the percentage overshoot will also increase.

And, setting time will also increase. So, it is not recommended to use a higher integral gain. And, if we increase the derivative gain, we can reduce the percentage overshoot. We can reduce the settling time and it has hardly any impact in the steady state error; that means, this does not play any considerable role in the steady state error, but it plays a role in the damping. So, it will affect the overshoot as well as the settling time.

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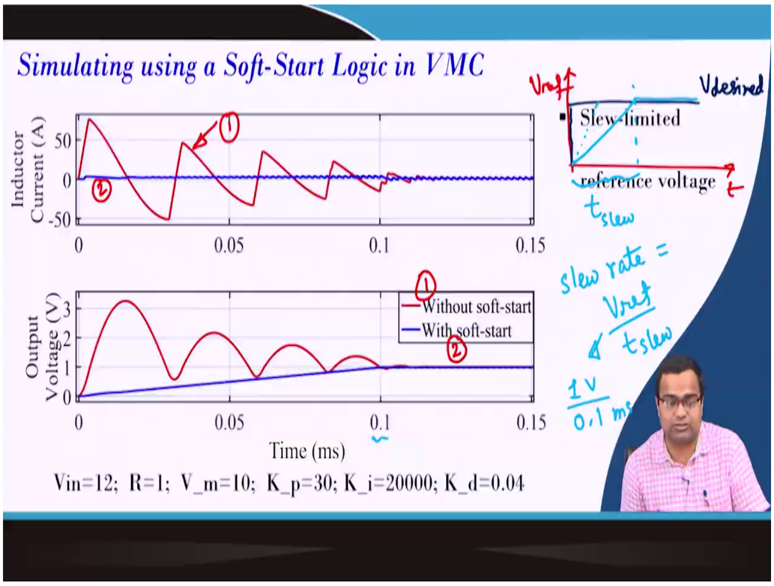

Now, my next question: can I reduce the start-up transient that we have discussed? Here I am showing a scenario. The red one which was the original one, the number 1, which is like a without start-up and the blue one is the with start-up. So, this is my with start-up. What I am doing? So, in the first simulation, if I plot the v ref profile; that means, I am just plotting my V ref. This is a reference voltage of the DC DC converter with respect to time. In the first case, ok. I am taking in the first case we are taking the V ref straight away to it is desired value. That means this is the desired value.

In the second case, what we are doing we are modifying this V ref and then reaching steady state here; that means, we are putting something like a slew rate. And, this time I will say t slew ok. So, what is my slew rate here? My slew rate, my slew rate will be equal to V ref by t slew. So, now, earlier it is like we are suddenly applying the V ref at the beginning and the error was large and that actually causes the whole overshoot undershoot and which is not acceptable.

But what we can do? We can now shape the reference voltage; that means, we can slowly increase the reference voltage until it reaches V ref. And, the slope of this reference voltage change which is like a ramp signal that is user defined. Because, if you want to make it very slow, then your converter will respond and you see there is no transient effect. So, in this case we have set how much, we have set 1 volt which is V ref divided by 0.1 millisecond. So, this is the slew rate in our case.

So, this is good and we hardly see any transient effect, but this may not be fast enough, because we may want to you know speed up the response. So, we may try to increase this slew rate. And, if we increase the slew rate, we will see the impact, but the next question how can we implement this logic? That means, if we go to the MATLAB. Now, this is where actually I wanted to show. In the MATLAB now instead of connecting this I want to connect this now ok.

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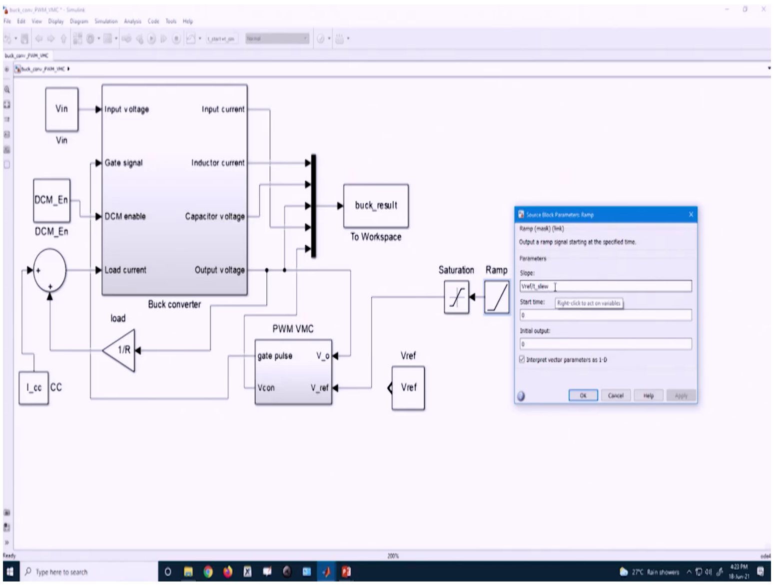

What I did? Now, I add a saturation block, because it is a ramp signal and ramp is V ref by t slew. So, I am defining my V ref and t slew is the duration that is my t slew. So, V ref by t slew, but it will keep on increasing. We have to stop when the voltage reaches V ref and that is why you put a saturation block upper limit is V ref, it cannot exceed beyond V ref ok. Now, we want to rerun this simulation and check what happens if we incorporate these changes ok.

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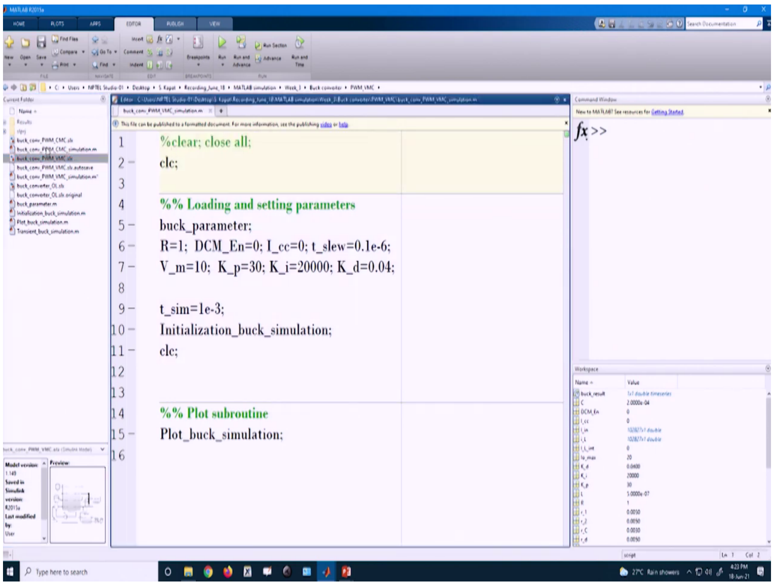

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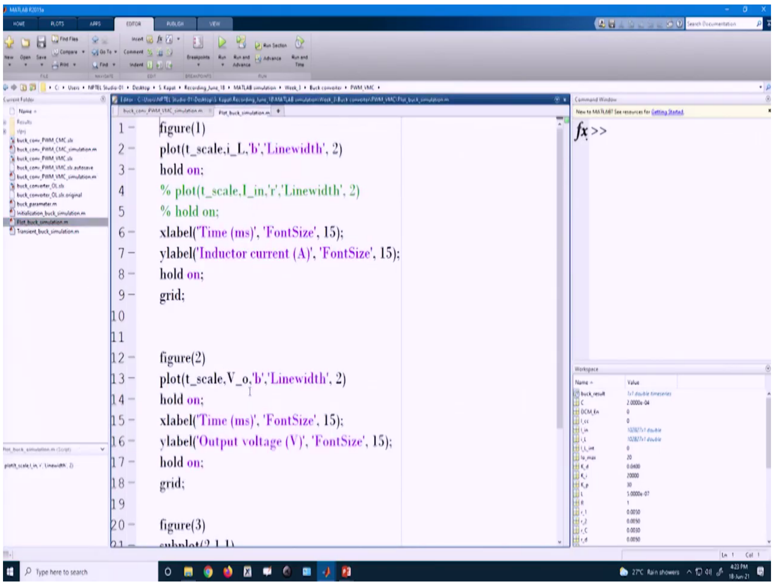

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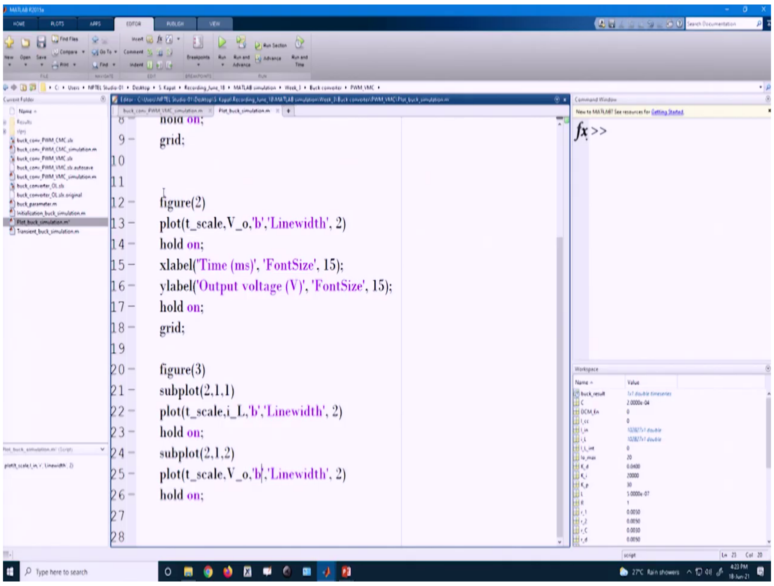

So, earlier it was the red colour now, I want to make it like a blue, so, blue. So, I am not made any change in the controller.

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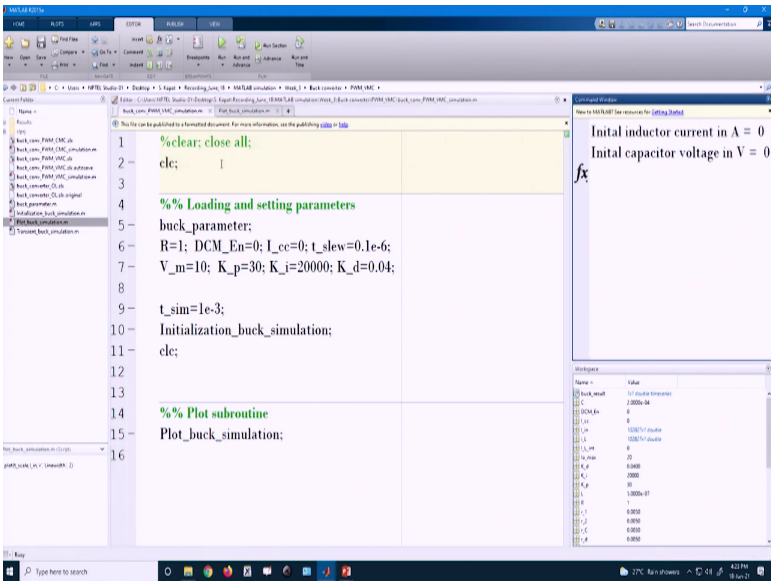

And, we want to start from 0. So, here we put a very fast slew rate that is why we would hardly see any. So, it is like a 0.1 microsecond; it is too fast ok.

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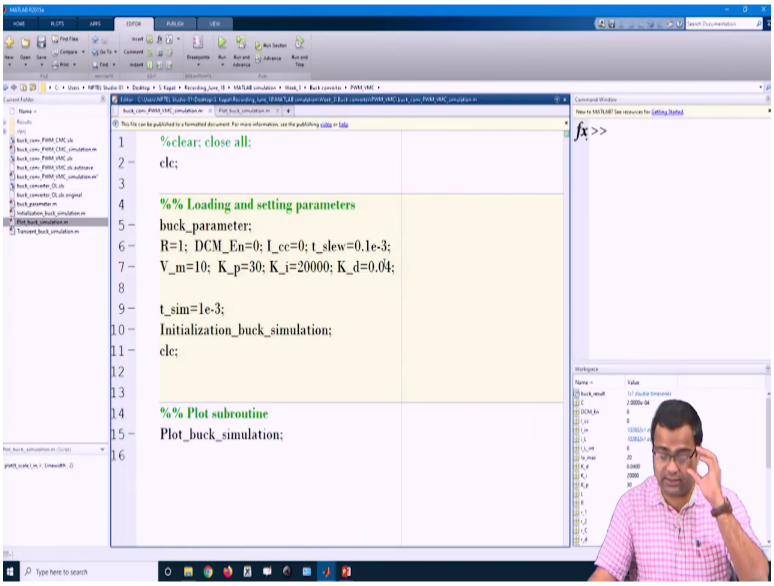

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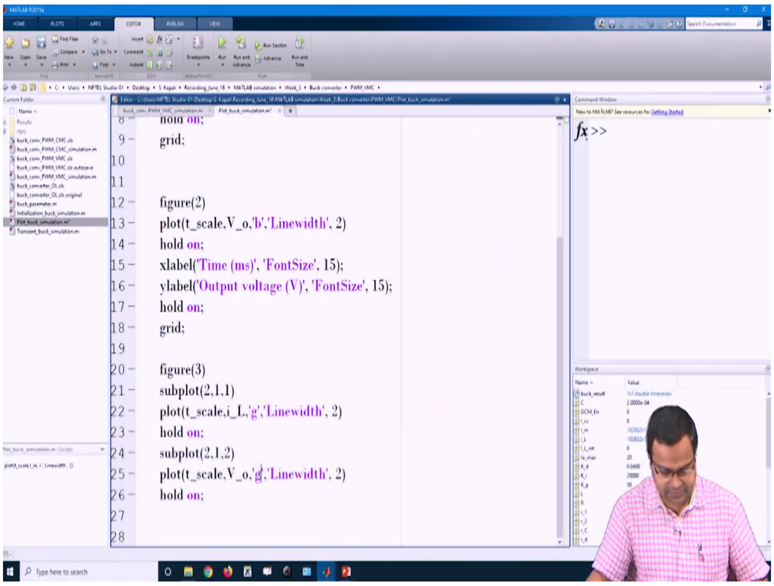

That means, it is same as originally, now we are putting 0.1 millisecond ok. So, now, let us change it to green colour and see the effect ok. That means, earlier, we set a very high slew rate, even though we are putting that block, but we are putting a very high slew rate.

Now, we are rerunning the simulation and see what happens? Thus, if the slew rate is too fast, then it is as good as that earlier, like we are putting a very fast V ref at the beginning.

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But, now you see we are putting a limit; that means, you know we are setting a limit in the V ref. And, now the voltage we want to change from 0 to 1. This means, if we go for up to 0.1 second, you see the green color shows that voltage is increasing from 0 to 1 volt, 0 to 1 volt yes, 0 to 1 volt in 0.1 millisecond, because it is in a millisecond scale.

That means, we can achieve this soft start action from here ok. The next task; that means you can change the slew rate so; that means, MATLAB it is slew rate we have already explained, that we can incorporate this block and you can change the rate of the slew.

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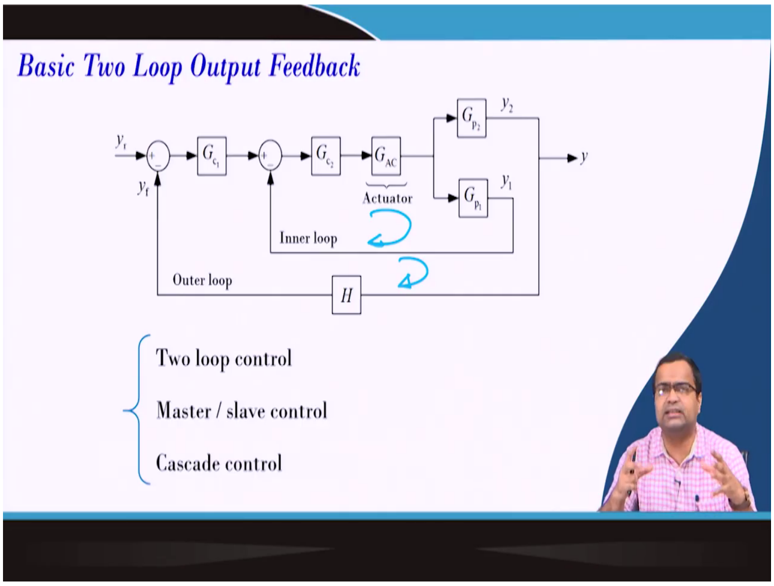

Now, we are going for two loop control. Now, in two loop control, actually we have an inner loop. This is my inner loop, and we have an outer loop. So, this is a basic architecture of a two loop control. And, where it is also called master slave control and cascade control right.

So, inner loop should be much faster than the outer loop in generally and there should be time scale separation. In fact, we will take a take the example of current mode control and when we will discuss there is a particular session, where we want to discuss what will happen, if two loops bandwidths are close to each other. So, whether how what kind of interaction we will find, and, such interaction what can it cause, that will also discuss.

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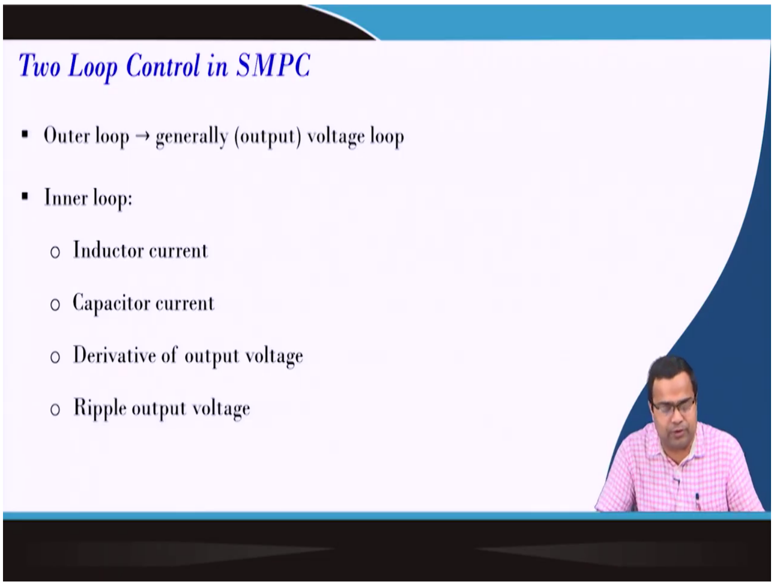

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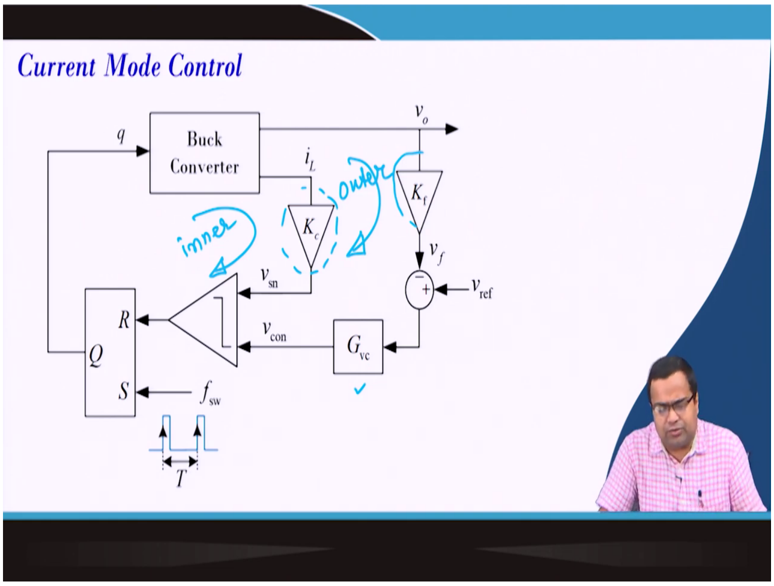

So, here in switched mode power converter, the two loop control outer loop are output voltage. Inner loop can be inductor current, capacitor current, it can be the derivative of the output voltage; sometime it is a ripple voltage, like in case of v square control. So, in current mode control, we have two loop control. So, this is my inner current loop, which is the inductor current loop and this is my outer loop, this is my outer loop and this is my inner loop.

If we put a current sense amplifier gain or current gain, current loop gain, that is K c and this is a feedback gain for the voltage loop that we discuss. And, then there will a voltage controller ok.

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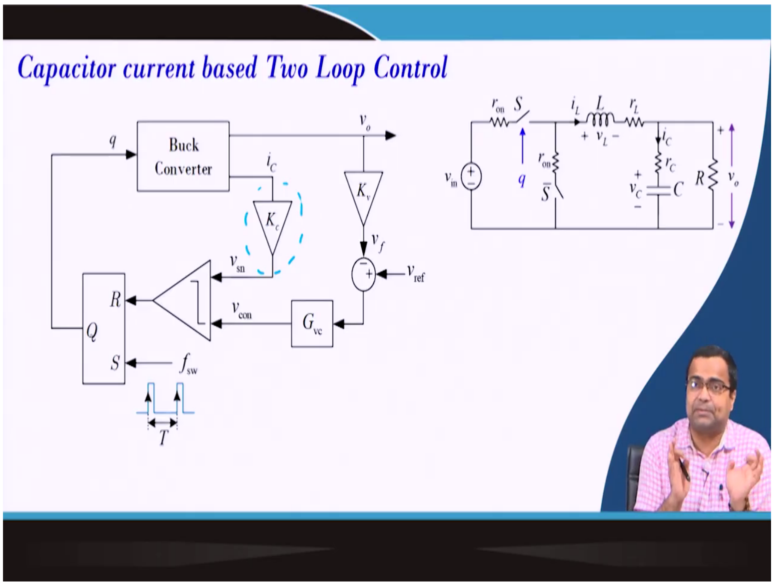

So, I will show you the implementation of this block. And, the alternatively, instead of an inductor current, we can also have a capacitor current control. In which instead of an inductor current, we can use a capacitor current that is also possible. But, it is very difficult to sense the capacitor current, because actually the capacitor current we should not put any resistance, extra resistance in order to sense correct.

Because, that can increase the ESR and that may not be a counter that may be counterproductive, in terms of the undershoot, magnitude of the undershoot and so on. And, that part also we will discuss when we talk about the output impedance.

So, if we want to put any resistance in the capacitor that can adversely affect the output impedance at a high frequency, that will also discuss.

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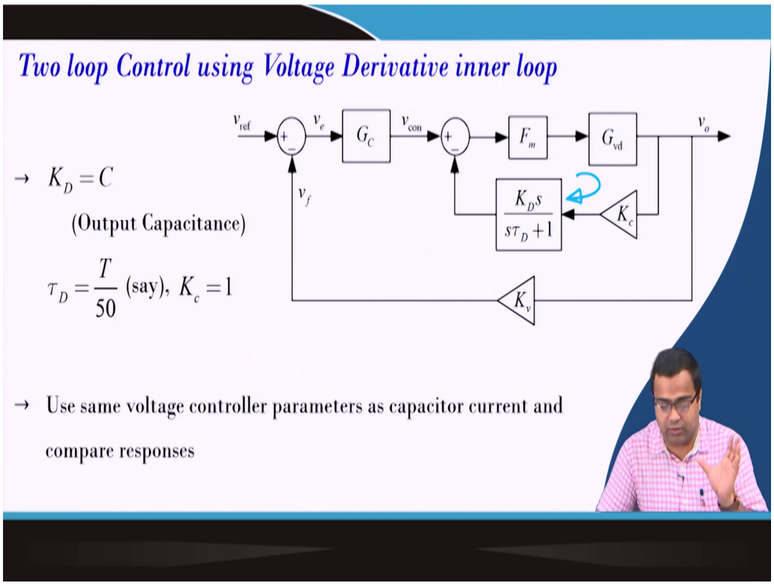

Another possibility the inner current loop can be a derivative of the output voltage; that means, this can also carry the information of the capacitor current for a buck converter, but this may not be a suitable solution for a boost where the voltage will have a non-minimum phase behavior ok. So, we have to be careful about this PID controller design the inner derivative loop for boost converter, because it has a non-minimum phase behavior ok.

So, derivative action then we have. If we consider this, we can actually compare the response of the capacitor current with you know and the actual current mode control we can compare.

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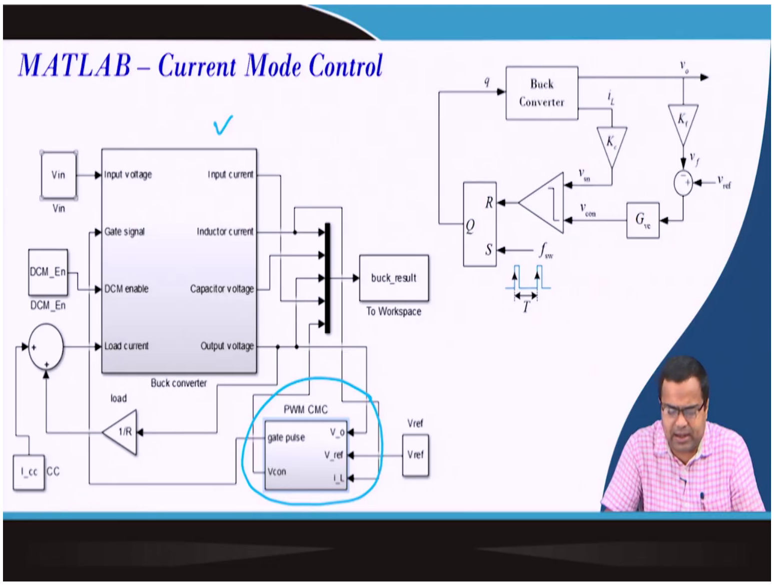

So, now first I want to show the MATLAB simulation of current mode control. And that we have already discussed. So, here now again I am introducing a controller here and which is my current mode controller.

And, we want to see what is that, because these blocks are already known to you and already these files are already discussed the MATLAB file.

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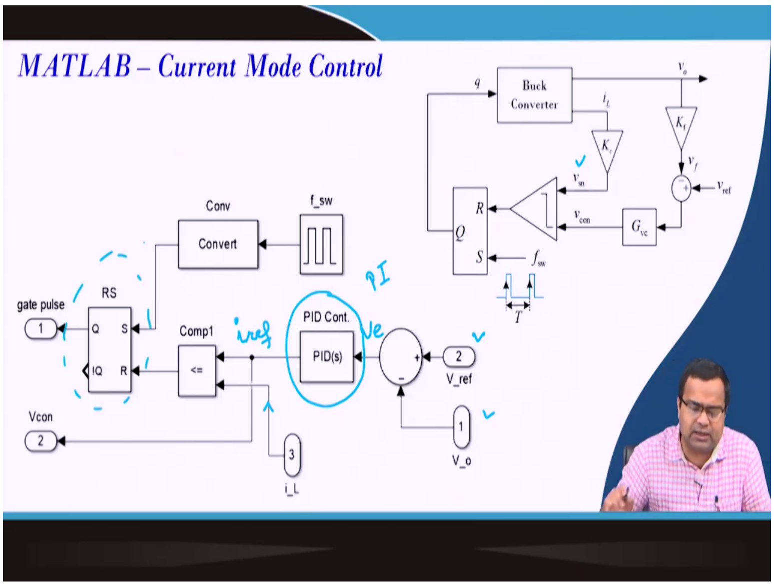

Here, this inside block again we have error voltage; that means, your reference voltage and the output voltage, then although I am showing a PID controller, but typically for current mode control, we can use a PI control or type-II compensator, but in this PID controller we can keep the derivative term 0. So; that means we can realize using a PI controller or you can use a separate transfer function block here.

Now, this is the reference current, this is my reference current ok. Or, in this case, it is my control voltage and here it is a reference current which is compared with the inductor current. Now, if we consider you to know in the last class we discuss the inductor current sensing; that means, typically the inductor current is like a sense voltage, equivalent to inductor current. And, this sense voltage is related to the current linearly with a scaling factor.

And, this r equivalent magnitude depends on if you use any sense resister or including the current sense amplifier gain. So, here I am just showing the basic structure of a current mode control where inductor current is directly compared with the reference current and reference current is the output of the compensator. And, this structure remains same because it is a trailing edge modulation ok.

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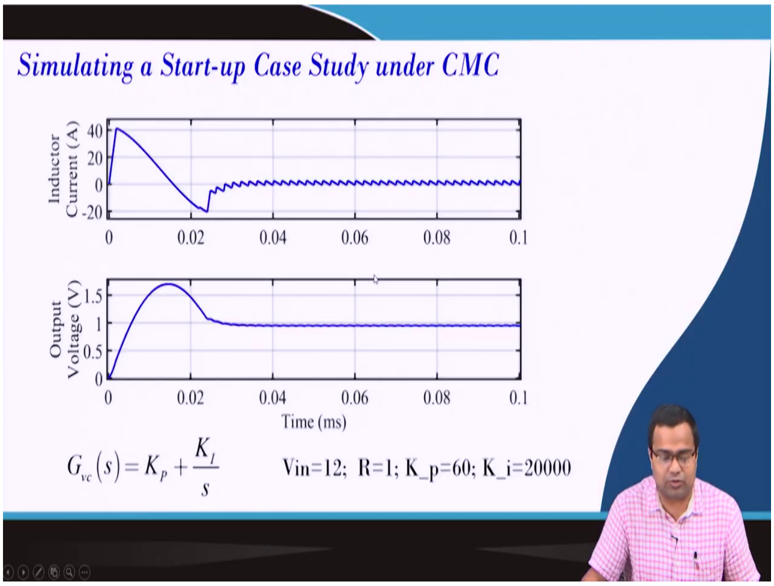

So, with this I want to show you the current mode of control implementation.

So, this was our voltage mode control ok. So, if you go to current mode control. In current mode control, this is what the block diagram I was showing ok.

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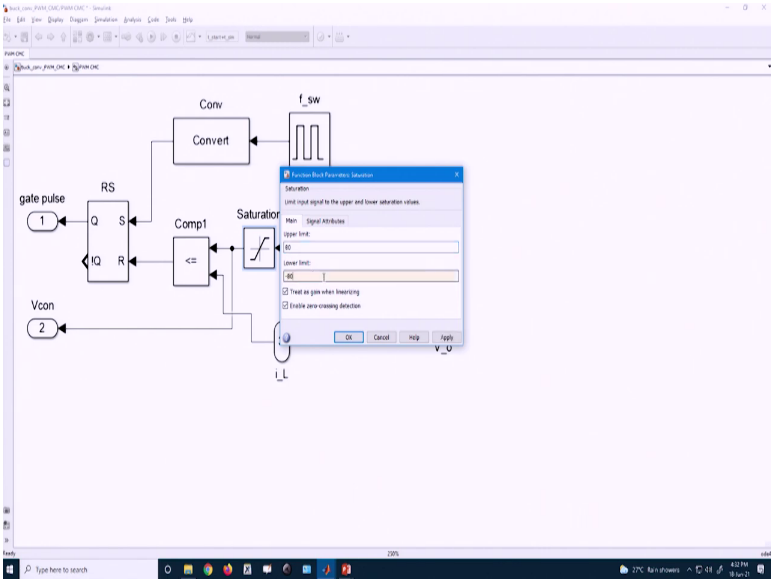

So, we can now ok, let me may be 80 or something. So, this saturation block maybe there may not be there because this is my peak reference current. This is my peak reference current and this peak reference current we can put a limit on the peak current, because it is a peak current mode control.

And, we can always put a limit on the peak current. That is why I am putting a situation block. And, since the current can go in either directions; that means, there can be overshoot under shoot in the current.

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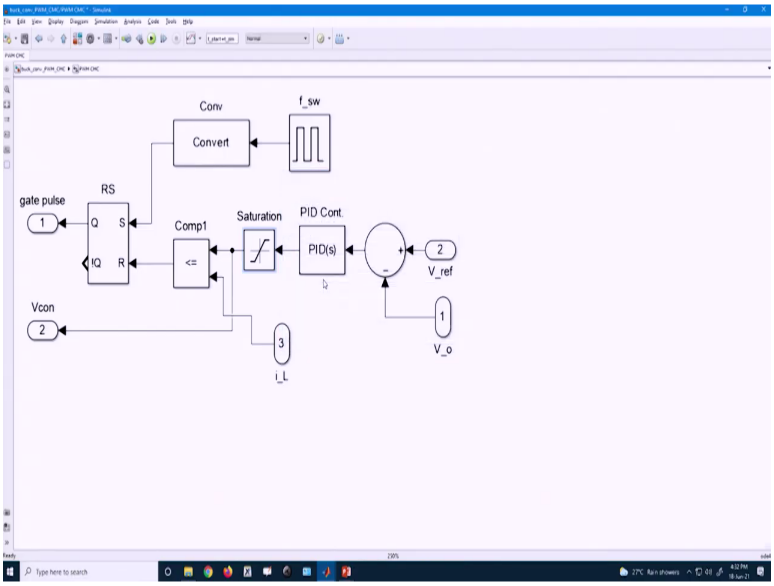

So, this saturation block should allow the limit in either direction. So, initially I put a very large limit so that actually the current will not get saturated; that means the control will not get saturated. And, it is compared with the inductor current. Now, I want to simulate this ok. So, I want to simulate. So, I will open this current mode control simulation file.

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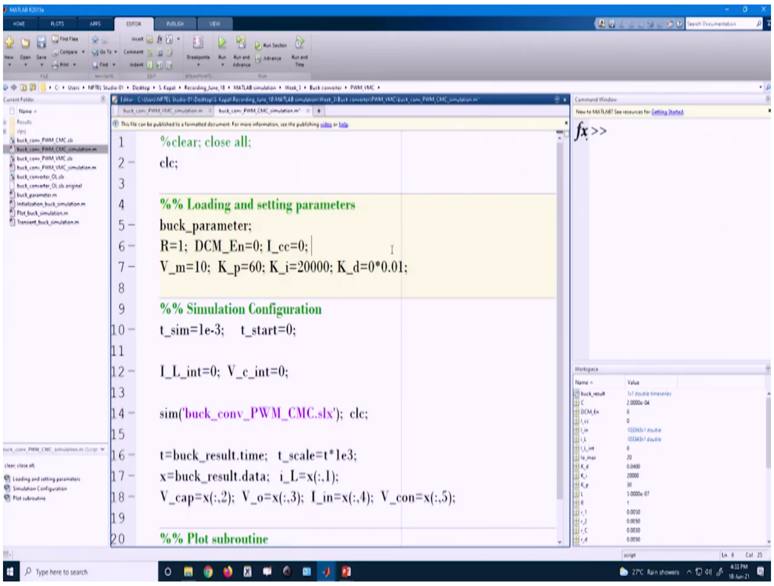

So, what I am doing here. Here, I took the pd controller to be 0 derivative controller to be 0 it is just a pi controller. Here, I do not need to put any slew rate limit, because I do not need any external switch. Why I am saying, because I use a simple V ref, but I still want to see, can I you know implement such soft star logic in current mode control, what are did in voltage mod, without modifying the volt reference voltage, which we did in case of voltage mode control ok.

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So, in this case, if I run again the start; that means we are starting, yes. Shall we? This is a start-up. The top one is the inductor current, and the bottom is the output voltage ok.

So, you will find, the output voltage reaches 1 volt much faster, that you know kind of within like a 0.025 millisecond; that means, 25 microsecond, but there is also huge peak current ok. And, that may not be acceptable; it may exceed the rating of the device. Now, this goes back to, but it is much better than voltage mode control, because we have a direct control over the current.

Now, the next question we want to set a current limit and see how can we improve this start-up performance without violating the current limit? The question is what value of current limit should we set? Again, it depends on you know we discuss about the power stress design. And, when we came up with the power stress design we identified, the peak current depends on what is my maximum load current. So, in this case we consider 20 Ampere.

So, we can go up to 25 to 30 Ampere. So, here I am setting let us say 20 Ampere current even or 25 Ampere current.

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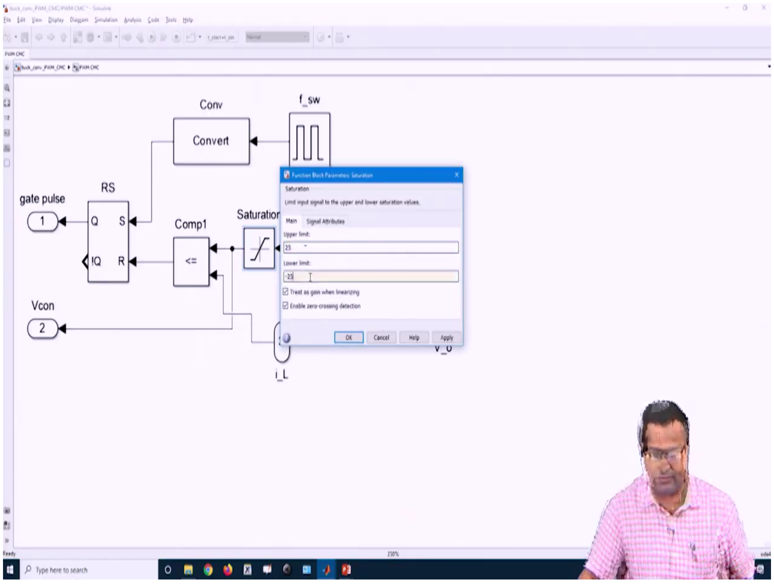

So, if I set a current limit of 25 Ampere and the same value I set like a minus side, also minus 25 Ampere. So, now, I am putting a current limit ok. And, I want to repeat the same simulation, but now with a different color ok.

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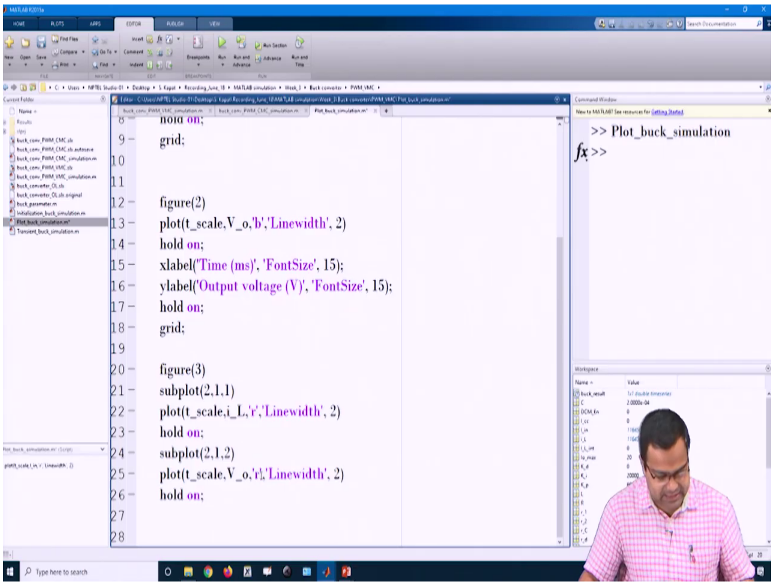

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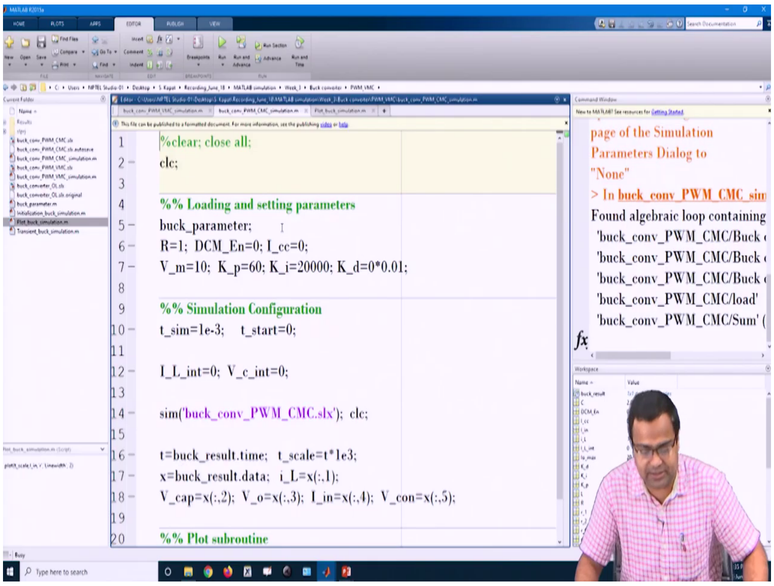

So, I am not changing anything. There is no additional soft start circuit, but what I am doing here. I am just repeating the simulation with a current limit ok.

So, I put a current limit of 25 Ampere both upper side and lower side and see whether can we yes.

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You will find still the current is limited to 25 Ampere, like it is nice that it is not exceeding

25, but there is a voltage overshoot, which may not be also acceptable because it is going around 1.1 volt. So, let us say if you are talking about a power supply for a processor, that 100 millivolt may be too high. So, we have to limit this; that means, at the beginning we can set the current limit to maybe 20 Ampere.

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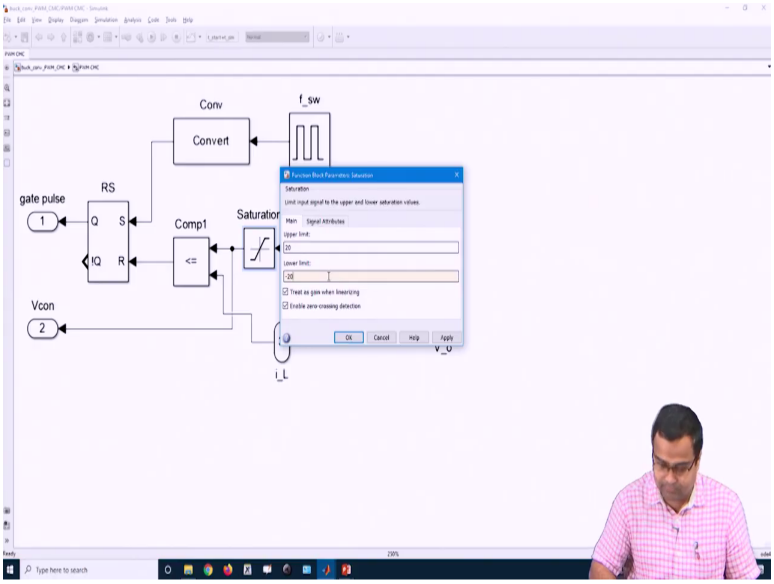

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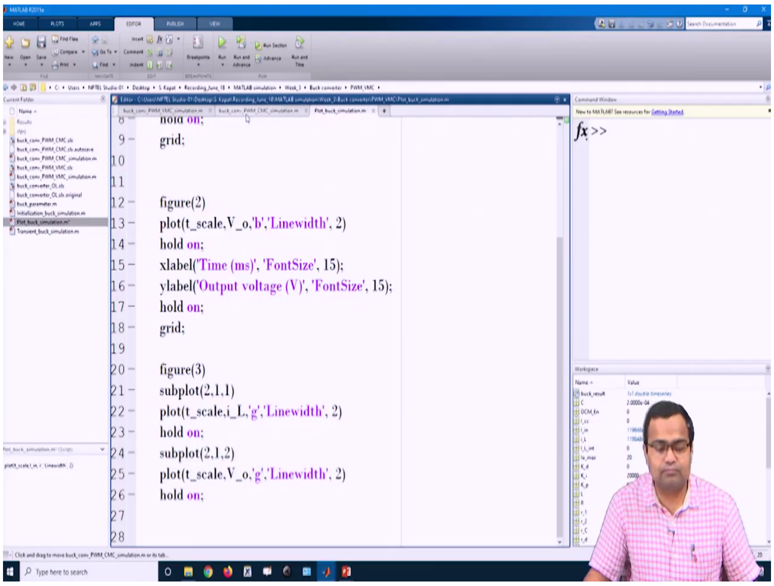

And, if you set to 20 Ampere for both up and down and we want to see, what is the impact; that means, I want to repeat the again this simulation. Now, I will use a green color and see ok.

So, now, what I did? I just put a current limit. In fact, there is a closed feedback loop. So, there is no problem, and I have decreased the current limit from 25 Ampere to 20 Ampere and this is my response.

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So, now you can see the start-up performance is significantly improved ok.

So, I can set that peak current limit up to the nominal load current ok. So, now, here we do not need. So, what I am trying to mean here, I am taking two loop control and in two loop control, the start-up can be taken care inherently by the controller itself.

So, you do not need a separate start-up logic, which was there in case of a voltage mode control, ok. So, by using the current limit, we can actually make a kind of soft start we can actually take the benefit of fast slew rate. Because, the voltage slew rate will be much faster and we have a comparative study here to show.

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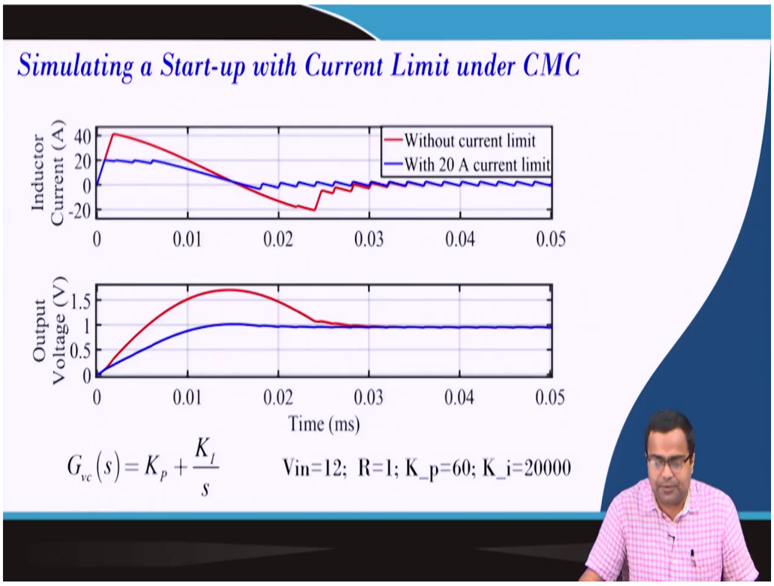

That means, for current mode control, this is without any peak current limit. And, this is a 20 Ampere current limit, and it is a very nice, you know, reaching its final value, without an overshoot, voltage overshoot and the current is also limited to 20 Ampere.

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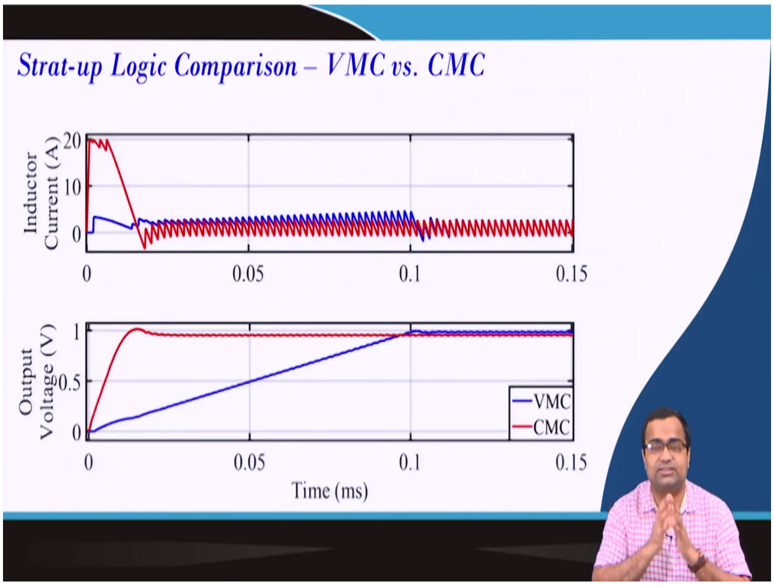

Now, if I want to compare the start-up logic between voltage mode control and current mode control.

So, you will see in current voltage mode control, though the current overshoot has reduced during the start-up, but the slew rate of the output voltage is much slower and this can affect; that means, you know, because you want to really speed up the start-up process. So, since we have designed the converter, the component based on the maximum current rating.

So, 20 Ampere current limit is much you know within the limit. So, why cannot we go up to that point and speed up the response? Rather than we limit the current to a very lower value. So; that means, I would say this current mode control start-up process can significantly improve or save the recovery, the start-up recovery time.

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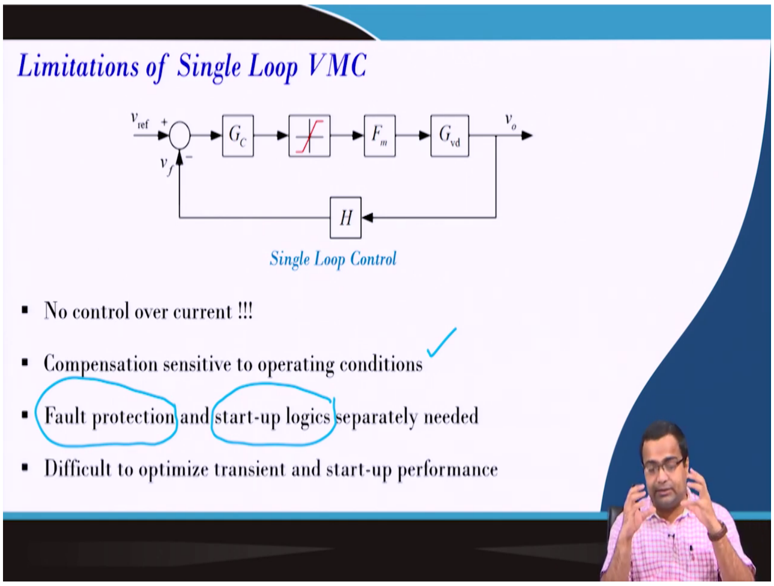

That means in single loop control no control over current, because there we have to limit the slew rate, because there is we have no control over the current. Though, in most of the IC the protection current sensors are used for protection purpose. So, we can take the advantage and to implement this current based logic for the start-up.

But, in typical voltage mode control, there is no control over current. The compensation is sensitive to operating condition, this part will highlight in the design of buck converter under voltage mode control. But, the fault protection and the start-up logics are separately needed. This means, we need this start-up logic in voltage mode control where, we slowly increase the reference voltage. So, you need an additional circuitry to do that.

And, if there is a fault; that means, the current can simply you know kind of you know damage the switches and the other device, that is why for the fault protection purpose, we need to put a current sensor. And, the start-up transient is difficult to optimize.

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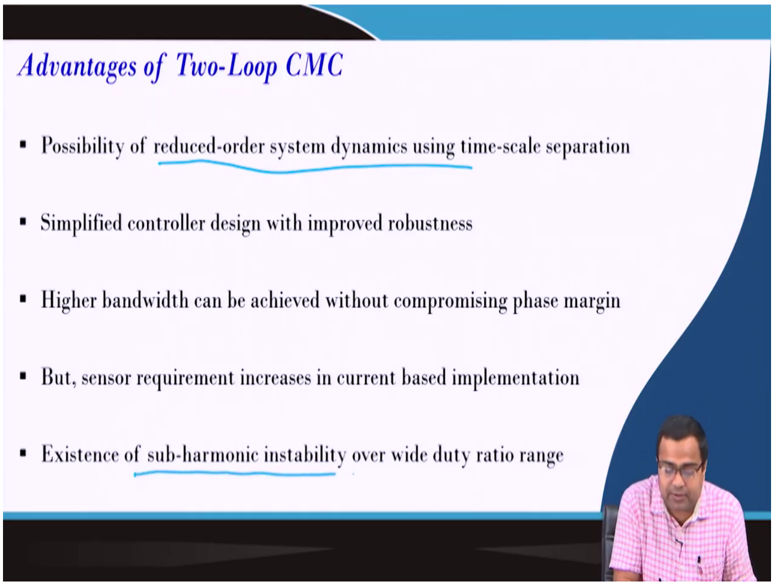

Whereas, in two loop control we can reduce you know first of all this part will discuss, because in two loop control we have an inner loop and outer loop and we want to make sure the two loops are widely separated in terms of their time constant. But because of this inner loop and outer loop concept, we can actually represent this converter to a first order approximate system.

So; that means, and we can and this will simplify the design process ok. The higher bandwidth can be achieved, because we are taking the advantage of the first inner current loop, but it requires everything comes with the price so, the sensor requirement. And, in current based implementation, we need a current sensor. And, also there will, I will also show the sub harmonic instability in current mode control, when the duty ratio exceeds 50 percent for peak current mode control.

And, we need to separately incorporate the compensating ramp ok, but in digital control and you know other modulation technique this problem can be resolved, that will also discuss. And, now using digital control implementation, we can estimate current, even we can estimate really very fast dynamics current. So, we can get the benefit of faster current loop without sensing current, those are possibility are the possibilities.

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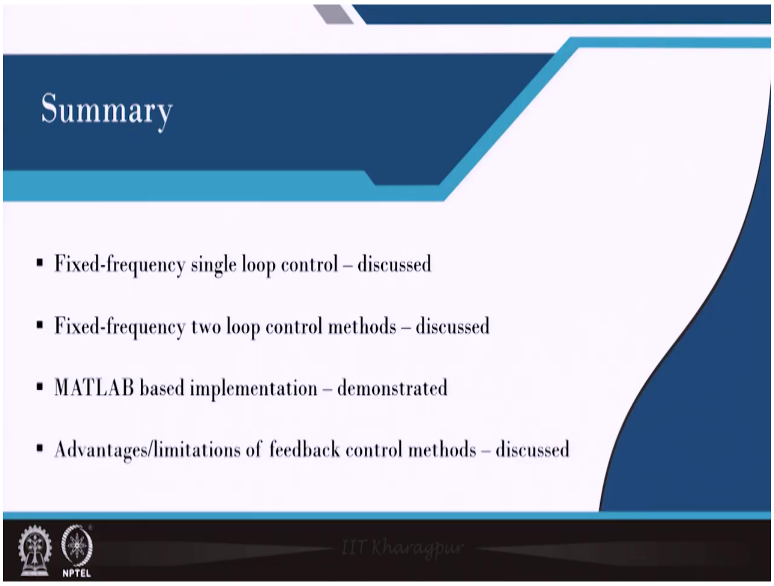

So, I want to summarize that fixed frequency single loop control is discussed. Two loop control method discussed, then MATLAB base implementations are demonstrated and advantage and limitation of feedback control methods are also discussed.

And, we will see more detail about single loop and two loop control design in the subsequent lecture. But today I want to give a glimpse of the feedback control and their implementation in MATLAB. With this I want to finish it here.

Thank you very much.