Control and Tuning Methods in Switched Mode Power Converters
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Module - 04
Variable Frequency Control Methods
Lecture - 21
Constant Off-Time Control Methods

Welcome this is lecture number 21. In this lecture we are going to talk about Constant Off-Time Control Methods.

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So, in this lecture we are going to talk about constant off-time control some basics and we have already discussed the modulation aspect of constant on/off time. So, in this lecture we are going to emphasize more on the control aspect. Then, we will talk about single loop and 2 loop constant off-time control, then problem with constant off-time control and what are the solution.

Then, MATLAB case studies of a buck converter under constant off-time control, and then constant off-time feedback state feedback control.

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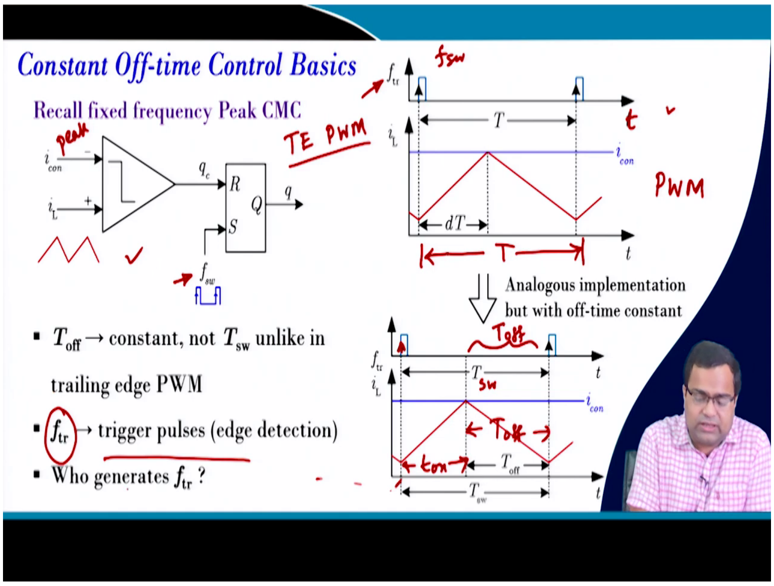

So, if we go to constant off-time control basics, we will first recall our fixed frequency peak current mode control. In fixed frequency peak current mode control, we have a control current and this is our peak current reference; we have this is our peak current reference, our peak reference.

And, inductor current is compared with the peak current and then comparator output is used to turn off this reset or the lag circuit, and that turn on happens by the switching clock here. So, this is trailing edge PWM, under trailing edge PWM that you have studied. And, this is under fixed frequency control and this is the waveform under peak current mode control where here, we have a trigger pulse. In this case it is a switching pulse which is used.

So, in this case, it is switching pulse. The edge of the switching pulse turn on the switch and the switch turns off when the current hit the peak current limit. Now, keeping the same analogy; that means, we want to again control the peak current; we want to use constant off-time control. Here, it is the same as peak current mode control, but in this case the time period, instead of time period in PWM. This is our fixed frequency PWM.

Here, our time period was constant; that means, you can see this time period was constant, but in this case our off-time is constant, this is our off-time, the off-time is constant ok. But, the basic like a fundamental of controlling peak current that logic remains same, but the fundamental modulation structure is different. And, here constant off-time you know off-time is constant that we have discussed. But time period is not constant.

So, any perturbation can actually change the on time. So, this is our control variable, because off-time is constant and on time is generated from this comparator. So, that varies and if that varies, then time period will vary right. And, here the trigger pulse that comes which is which turn on the switch, that comes from the monoshot timer, because if you take this particular phase in this phase. So, here it is switching frequency is not constant. So, it is T sw ok.

So, in this trigger pulse, this off-time is generated from a monoshot timer; that means, when you enable the monoshot timer, the monoshot timer remains activated, it remains activated for the duration of T off. And, once that T of time is elapsed, then the monoshot timer is turned off and, based on the falling edge trigger, we can turn on the switch; that means, the switch turns on when the monoshot timer finishes its counting.

So, that is a trigger pulse. So, trigger pulse is the falling edge of the monoshot timer ok. Then, the logic remains same; it controls the peak current. So, who generates the trigger pulse that we discuss.

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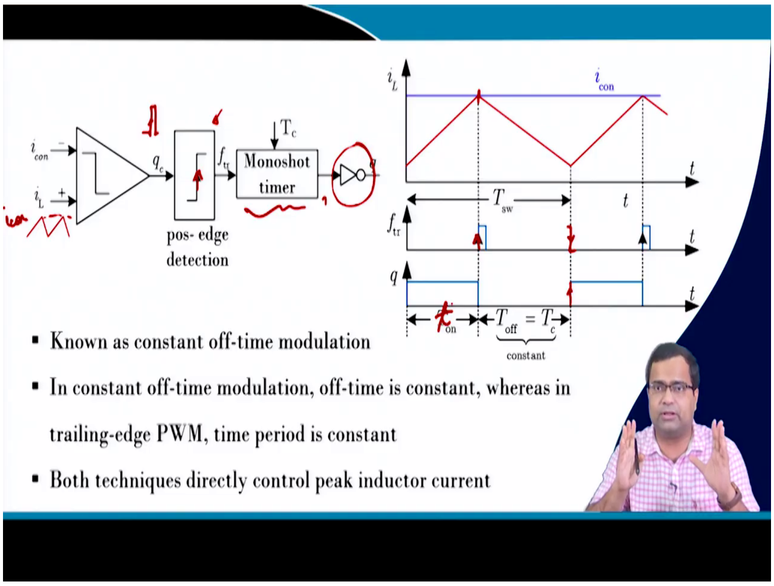

The trigger pulse is generated by a monoshot timer? That means, here first it detect the positive edge; that means, once the inductor current tried to cross the peak current limit, this is my control current or the peak current, then the q c goes high ok. And, when the q c goes high, this edge detection circuit detects the edge and this trigger pulse activates this monoshot timer.

And, as long as the monoshot timer is on, this is you know NOT; that means you have inverted the logic because you have to turn off the switch. And, this switch remains turn off I mean as long as the monoshot timer is activated. When the monoshot timer turns off; that means, finishes its counting, then we again turn on the switch. So, that is the logic ok.

So, this is the logic and that we have discussed the monoshot timer whenever this hit the limit. The monoshot timer is activated. And, when the monoshot timer finishes its counting, then this edge is used to turn on the switch, turn on the switch. So, this is known as constant on time, off-time current mode control, which is analogous to peak current mode control. And, again we have discussed that here time period can vary if there is any perturbation in the on time.

So, here on time can vary when the converter operates, because this is not a constant quantity. Under steady state they will reach more or less constant. So, both technique in peak current mode control for fixed frequency, and the peak current mode control like constant off-time, they control directly the inductor peak current.

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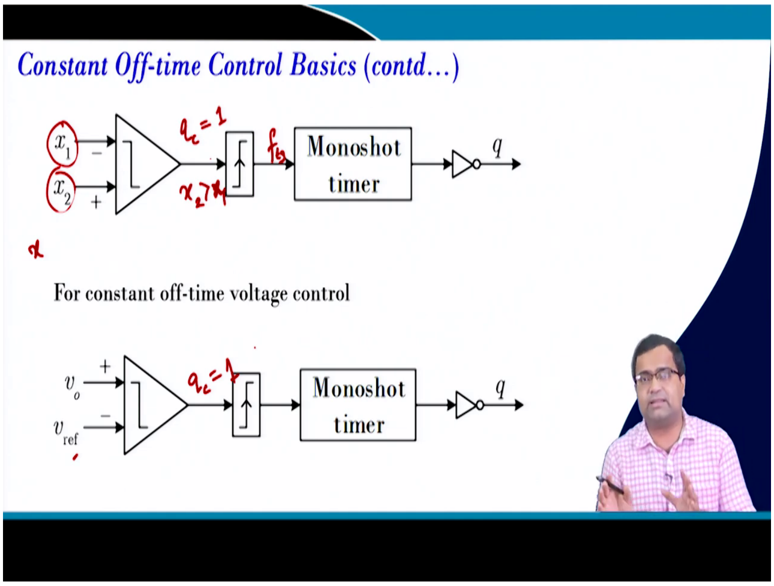

Now, what is the basic logic? Instead of current, we can also compare voltage or you can take the combination of current and voltage. So, if you take two signal x 1 and x 2. And, if whenever the x 2 is higher than, whenever you know whenever x 2 is higher than x 1, then this comparator actually goes high ok. And, whenever this happens, then this positive edge generates a trigger pulse and that, you know, activates the monoshot time.

So, in case of voltage control, we simply replace x 1, and you know x 2 by v 0 and v ref so; that means, whenever v 0 is greater than v ref, then this output should be high, this output of the q c should be high ok. For example, if you if the monoshot timer was turned off, that time the voltage will fall ok so, voltage will fall; that means, during the off-time.

And, when the monoshot timer finishes its counting, then the switch is turned on and the voltage keeps on rising. The whenever voltage rises and it tried to cross reference voltage, then this switch goes high ok. And, then this monoshot trigger pulse activates the timer.

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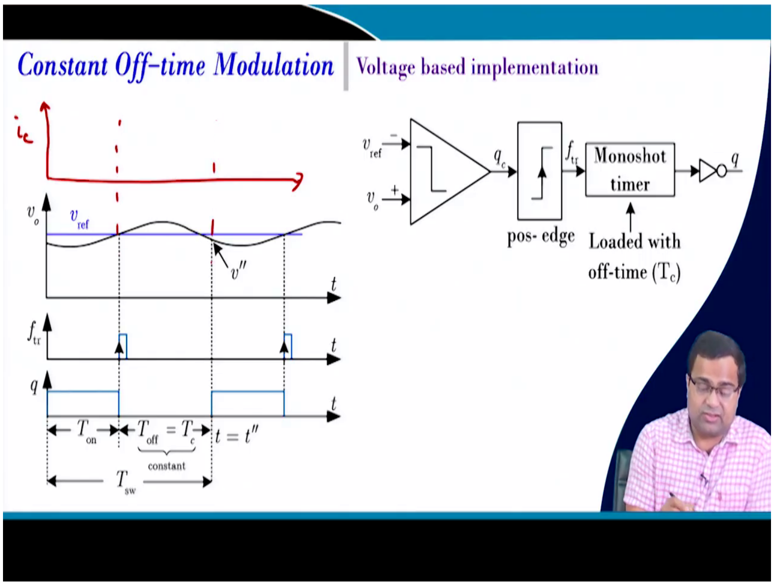

So, if you take the voltage waveform. So, this is exactly what I have discussed. Whenever the switch is on, you know initially voltage will fall because, if you draw the capacitor current, then you will understand that if you draw the capacitor current of a buck converter. So, like this ok. So, whenever the switch is on so, this is sorry if I draw the capacitor current.

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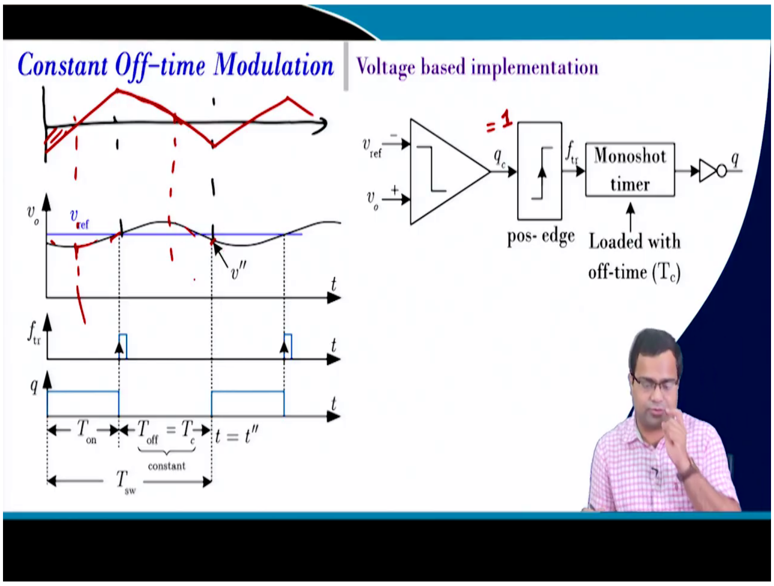

So, let us draw this capacitor current and we will demarcate this duration, whenever switch turns on the capacitor current is negative. So, it rises then it falls, sorry it falls like this again it rises, again it falls like this. So, as long as the capacitor current is negative, the voltage will continue to fall, the voltage will continue to fall. Whenever the capacitor current becomes positive, voltage will rise.

Similarly, here whenever this capacitor current is positive, then voltage will rise so when it is negative it will fall. So, here the logic is that whenever the switch is on then voltage will rise after some time and when the voltage crosses v ref then switch turns off. That means, this comparator goes high and when is goes high, it activates the monoshot timer and the switch turns off.

And, when the switch turns off after some time, the voltage will start falling and again when the monoshot timer finishes its counting, then again switch turns on. So, this process continues.

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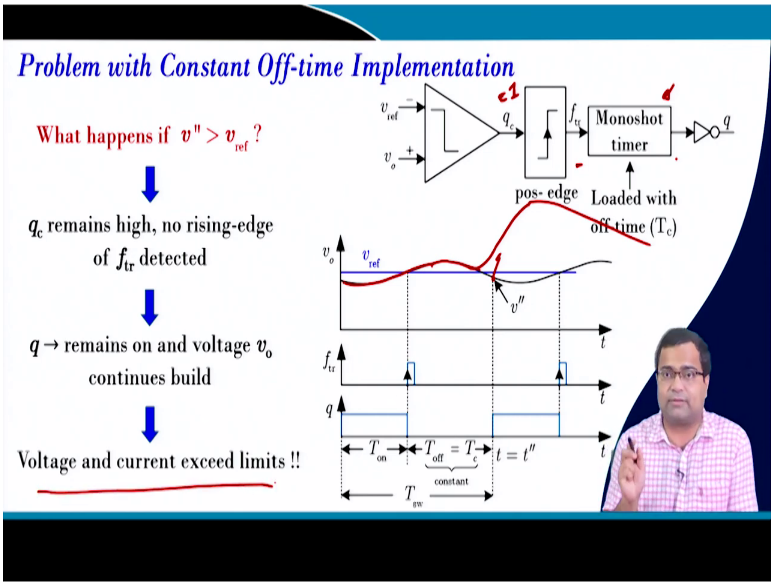

Now, there is a problem which we discuss in under the context of in the context of constant on time, we have discussed. What is the problem? That means, if v 2 dash, that means this voltage after switch was turned on we found that; that means, whenever the monoshot timer finishes it is counting, then what is our expectation? That because the switch was turned off during the activation period of the monoshot timer. So, under steady state, it is expected that output voltage should be go should go below reference voltage.

Because the switch was off, but consider a scenario when you have a step down transient, when the output voltage is already high and your capacitor current is positive. So, it has it will take some time for you know come to 0. During that time the voltage is high; it is much higher than the reference voltage. During that time, even though you turn off the monoshot timer, the output will continue to become higher, higher than reference voltage.

So, this can go up, that means, I am talking about the scenario when the load step of transient the voltage will simply go up like this. And, if it is high, then the comparator output is high, and that means it remains high. And, if it remains high, no edge is detected, there are no edges right.

So, the monoshot timer cannot be activated and, if the monoshot timer is not activated that means switch remains on because, monoshot timer act is to turn off the switch remains on and the switch, remains on the voltage will keep on rising, so, instead of because it is step down transients.

So, you have to you have to slew-down the current, but instead of that, current will actually go up. And, this process actually it takes the voltage to this input voltage; that means, huge it increases significantly and the inductor current can saturate the core ok. So; that means, we have to be very careful about this constant off time.

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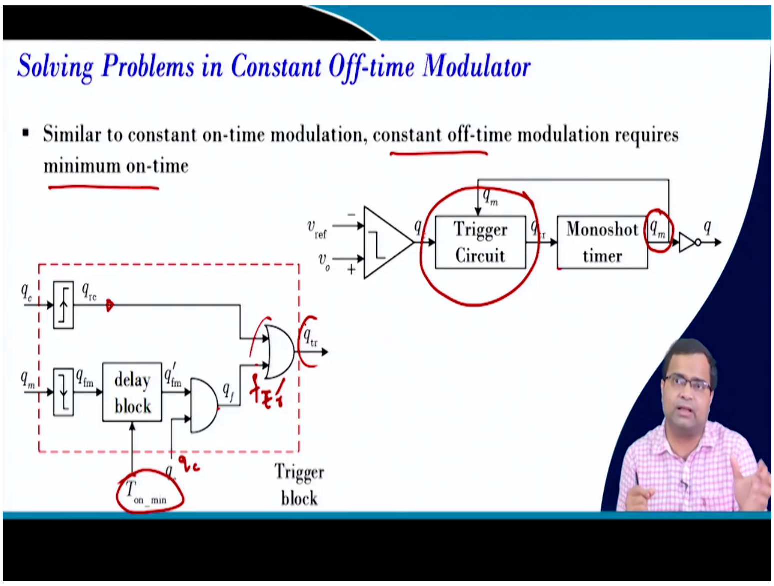

So, what we have to do? We need to introduce a minimum on time. In case of constant on time we have introduced minimum off-time, in case of constant off-time we have to introduce a minimum on time. And that means, we need to create a separate trigger pulse and that we will discuss, which means we have to check the comparator status.

That means, if you take this q m which is the output of the modulator, which was supposed to go high, which is supposed to go low sorry whenever the monoshot timer is turned off; that means, q m should go from high to low when the timer actually finishes its counting.

And then it detects the edge, and that edge is delayed. And, after the delay and this delay actually will load with minimum on time, and if it finds that after the delay, the still q c is high; that means your output is still higher than v ref, then it actually takes this it generates another trigger pulse.

So, this is another trigger pulse, another trigger pulse, and then it ended with the original. So, we have used earlier this trigger pulse. Now, here we are generating a falling edge trigger pulse and which is a delayed signal, and this will take the OR operation of these. That means, even if the switch output is higher, it will check after the monoshot timer finishes its counting and it checks. After some time it still remain high then you have to forcefully turn off the switch ok.

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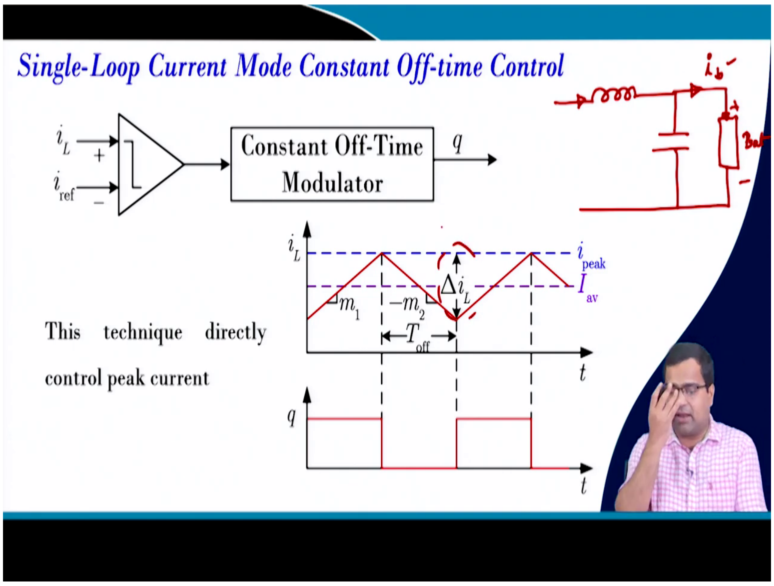

So, that logic we will see when we will go to the MATLAB simulation. In single loop constant off-time control of we can use both current single loop as well as voltage single loop. So, in the current single loop, if we want to control the peak current, and this is particularly important when you are going for a battery charger right. So, the battery charger the voltage of the output voltage at the battery terminal, it is not in our hand, ok.

Because, it is decided by the battery is decided by how much current you are putting in the battery and the terminal voltage of the battery will actually go up. So, we do not have any control over it. But, suppose if we take a buck converter, there is an output capacitor, and here you are putting a battery. Now, this is our battery. So, you have a positive and negative terminal for the battery, if so, this is my battery.

So, we want to make sure that this current, which is going to the battery, should be constant. And, that can be achieved under steady state, if we ensure that average inductor current is same as the required battery current, because the capacitor average value should be more or less 0.

Then, we can because it is slowly varying the voltage, then we can ensure that we can supply the average current, which is required by the battery. And, we can do it, because this is a ripple parameter right.

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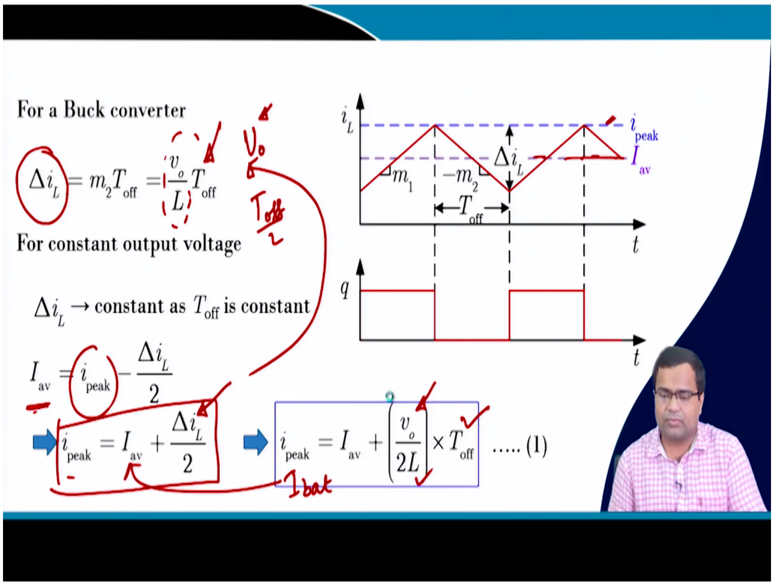

And, this ripple can be written in case of a buck converter. What expresses the ripple? If you write in terms of falling slope, it is m 2 by T off. And, the m 2 is v 0 by L, now this v 0 output voltage, what is the output voltage if you want to connect to a battery terminal, it is a terminal voltage of the battery ok.

And, that you can measure right, so, by measuring the terminal voltage and assuming, because setting T off is constant right, because you are setting the T off and the inductor is assumed to be known. So, you can find out T off by L, I am not saying it is exactly known, but it is reasonably known, because it is set from the design, then output voltage can be measured from the terminal voltage of the battery. And, then if we know output voltage, then we can know what is my delta i L right?

So, what is if you know the delta i L, then what you have to do? Your required average current is nothing but my peak current. This is my peak current minus delta i L by 2. This is my average current. And, I want to make sure of that. So, it is an indirect control of battery current by means of peak current. Because we want to control the average current, but in order to control the average current, we are controlling the peak current.

So, if we can make sure if we can, that means this is a required average current. So, the peak current can be found. So, this is given by the battery. So, this is my battery current ok, this is my battery current. And, delta i L by 2, I told that this will be calculated from here.

The voltage of the terminal of the battery is slowly varying. So, it is more or less constant for switching time period, because it varies at a very slow pace like you know battery terminal voltage. Because converter can operate is operating, let us say 500 kilohertz, whereas, the battery terminal voltage varies in terms of minutes ok.

So that means it is a very slow varying process and under that slow varying, if you take the sample of the output voltage. So, then you can compute the ripple directly by measuring the output voltage sample, and you can set the average value of the ripple and then you can set the peak current, by that way you can control the average current ok, and this is known.

So, that means this is known, this is more or less known and this we are taking the sample from the battery terminal voltage. This technique can also be used in LED driving. In fact, many commercial product use that. So, if you use either boost or buck converter average current control of the led, so, you can use the constant off-time control, because we will see in the subsequent lecture, that constant on time as well as constant off-time control has inherent current loop stability.

So, whatever duty ratio will take, it will always remain stable, unlike in peak or valley current mode control, where we will find there is a duty ratio range for current loop stability, and you need to put a compensating ramp. Here you do not need a ramp compensation. So, you can very effectively control the average current by controlling the peak current ok.

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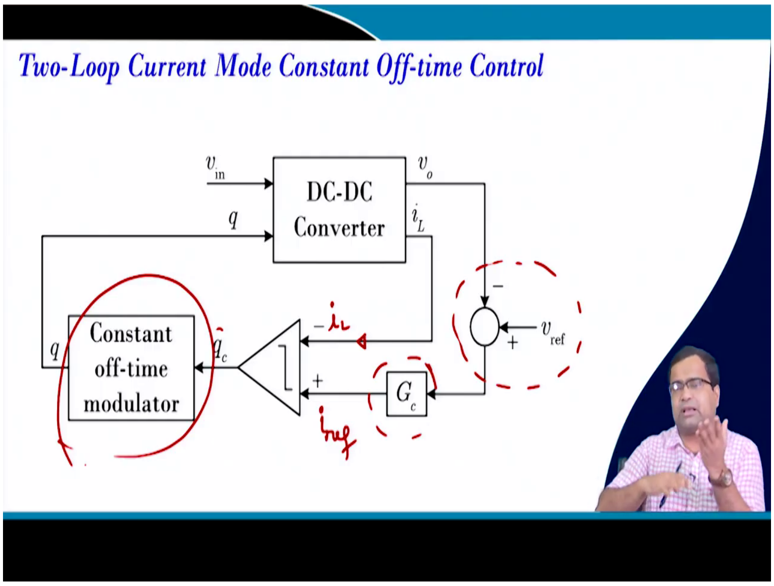

Now, we can also talk about two-loop control. It is current mode control. So, similar to our traditional current mode control, we will have an outer voltage loop. And, then this is the voltage controller, and this is our inductor current and then after the inductor current, this is like our reference current right.

Reference current this is our inductor current, then output of the comparator goes to the constant off-time modulator and that we have discussed, it will also have a minimum on time. Then, we can implement current mode control. So, the biggest advantage here we will see in the simulation result.

Since the current loop is stable, there is no instability problem ok. And, I will show you the supply transient as well as the current loop stability is very like excellent. Because, supply transient even in current mode control is very good, but here since there is no stability problem. So, you will not find any almost no change in the output voltage, even though the supply can drastically vary.

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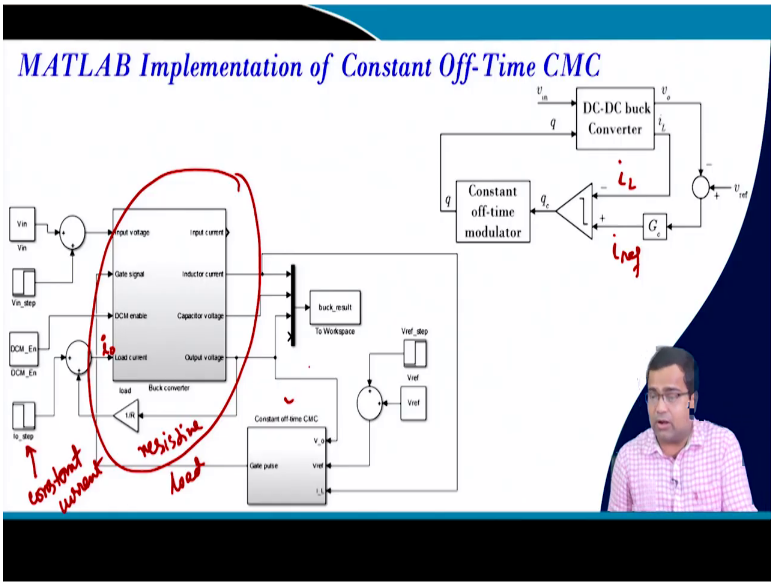

So, I want to show you the MATLAB implementation. So, again, it is a two-loop control current mode control. So, this is our inner current loop, this is our reference current, which is coming from the outer loop. And, this is the block diagram which I have shown for many simulations. The overall block diagram this block is the converter power stage. And, it is driving a resistive load right; we have discussed that resistive load, but we can also add a constant current load.

So, like we are back because if we want to apply a load transient, we can apply a constant current load. In fact, we can also apply a constant resistive load as well. So, you can program this. And, this is the actual load current which is going to the converter. Now, this block, what is this?

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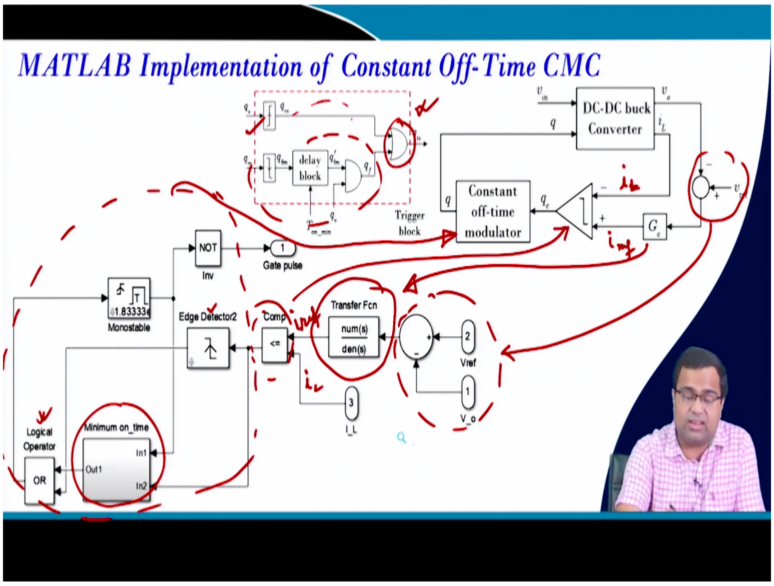

So, if we go inside this block, this is the transfer function where we can set the compensator, because this is this compensator that we talked about. And, you can see this reference block is nothing but our this block here, the which generates the error voltage ok. And, here we are using the inductor current.

So, here this is like our i ref and this is our i L. So, these two are compared and we have discussed this is i L this is i ref ok. Then, this is our comparator that we have discussed. So, this comparator is nothing but our this comparator ok. Then, this whole block is our constant off-time modulator. So, this block is our constant off-time moderator. And, the first block will be the edge detection circuit, which is here, then it will have a minimum on time logic.

And, the OR gate, although you put separately, but actually this is the OR gate. So, this gate is here ok. And, only this block inside it is there, and, if you go inside, this is the block.

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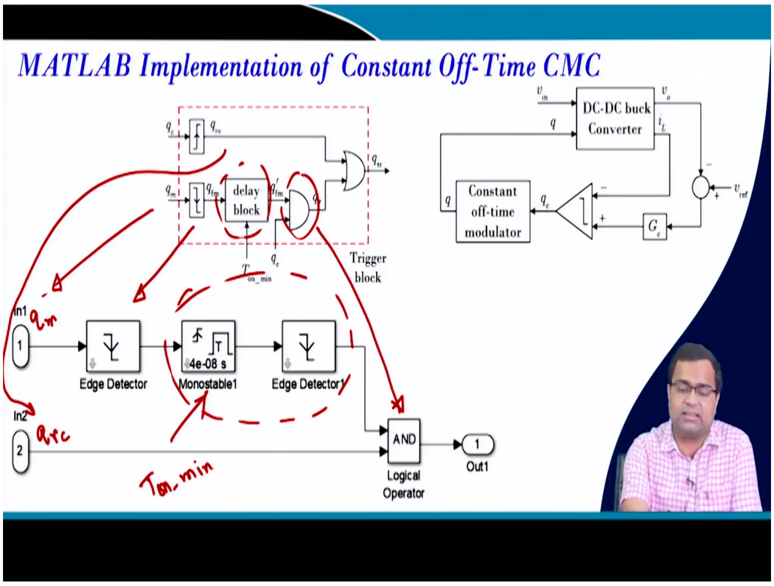

So, here it takes the negative edge; that means this is my q m analogous to this and this is my q r c which is coming from here ok. This is the AND gate which is here, and the delay block this is the edge here, and the delay block is implemented using this combination, the delayed block. And, here we are setting the minimum on time, minimum on time ok. So, if we go ok so, this block is a monoshot timer because we are delaying by the time well.

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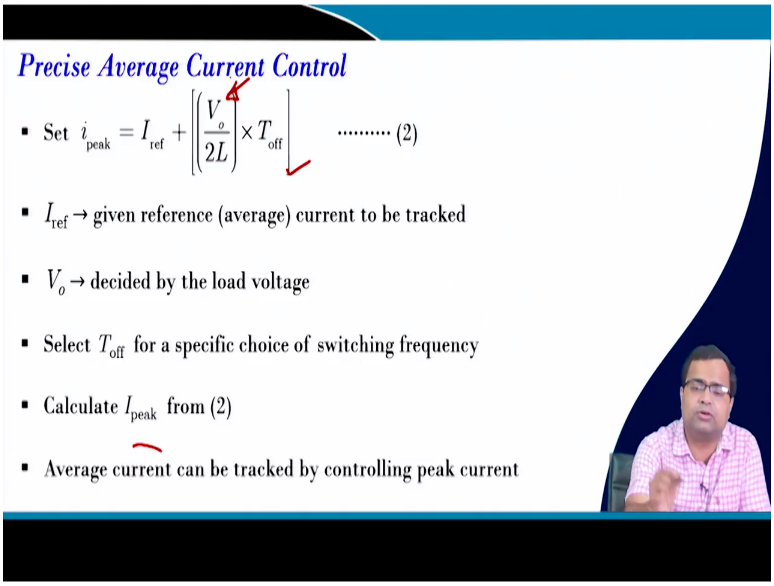

Now, if we want to do precise current average current mode control which you have discussed, we can set a reference current which we need to control, but ultimately it is constant off-time control where we are controlling the peak current. By controlling peak current, we want to maintain the average inductor current to its desired value, which is I ref.

So, V 0, if, suppose if you connect, if you take a buck converter, where the inductor is connected at the output terminal and you want to control the current, it may be LED driving application. Where the terminal voltage which is connected with the buck converter is a LED string voltage, which it is it will be known, because it consist of the forward voltage drop ok. It will be reasonably known ok, then T off so, we can calculate peak from this equation ok.

And, then we can implement this logic, because this will be more or less known from the LED string, this will be set by us and this is our inductance value which we are assuming will be more or less known there will be variations in the inductance value. But, we can actually adjust and we can make that reference current I mean inductor. By controlling the peak current, we can more or less maintain the average inductor current to its I ref value.

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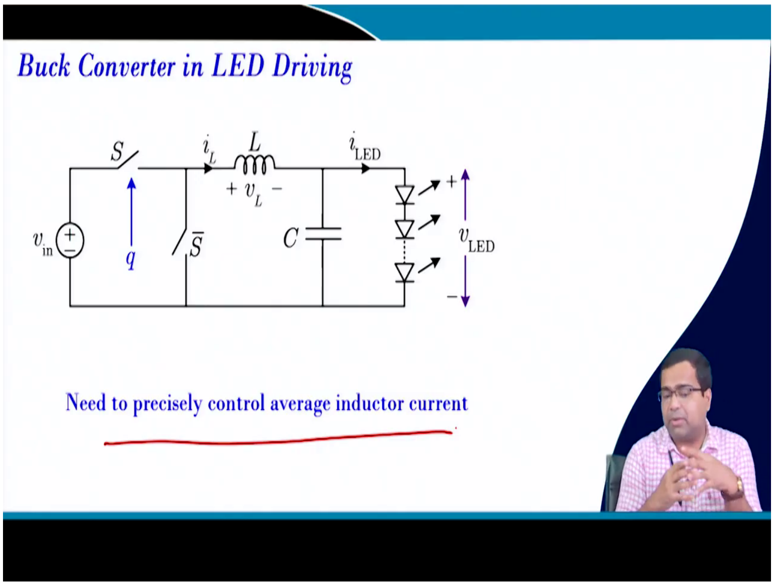

And that means we need to precisely control average current. Because if you go to traditional average current mode control, which required to you need to put a very low bandwidth current controller, in order to extract the average current from the inductor current so, that will slow down the bandwidth of the current loop. But, in this technique there is no as such averaging method is to extract the average current or neither we are applying any low-pass filter.

So, it is the sense current, which is actual inductor current and you are applying a peak current logic, but you still can obtain the average current control ok.

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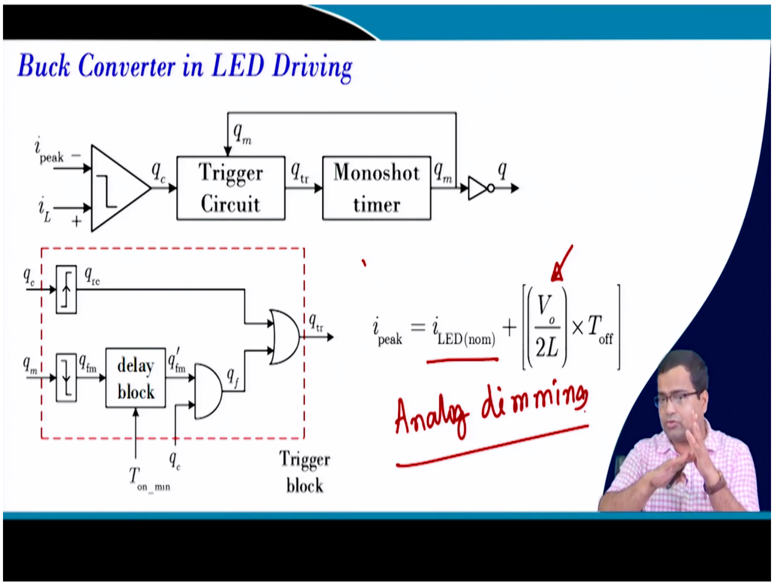

So, this LED driving we can say monoshot timer, all these blocks are known. Now, if we want to control the LED nominal current, then we need to set the peak current accordingly by setting the terminal voltage of the LED string volt. But, one thing I have not mentioned, this is for this works fine for analog dimming, analog dimming of the led,

But, if you go to PWM dimming or in that case that current you know the LED string is getting connected and disconnected, that only by controlling current will not be sufficient. Because, during connecting and connection and disconnection phase, during that, like you want to connect the LED string and also you want to disconnect.

So, during this process of connection and you know, and also removing the voltage overshoot undershoot in the capacitor can cause a significant, flickering current and in many cases it can damage the led. So, we need to consider some other aspect, but for analog dimming, this technique will work fine.

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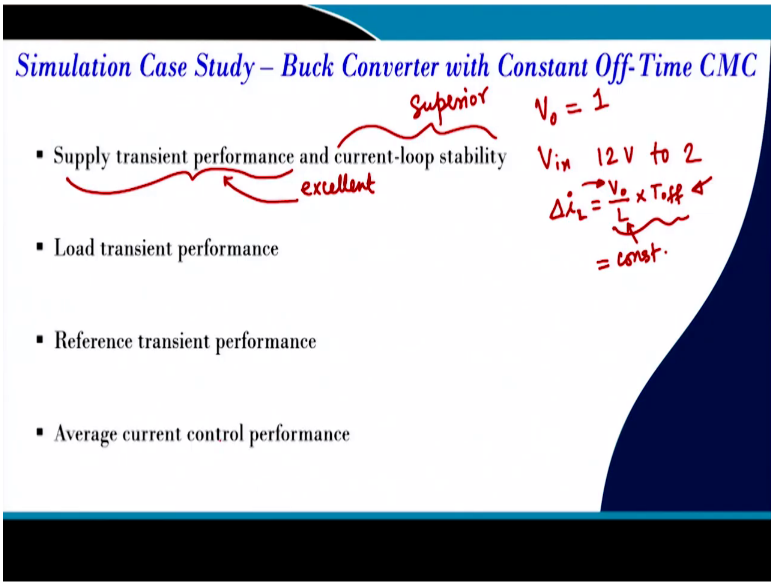

So, I want to show a few simulation case studies, like a supply transient performance and the current loop stability. So, here I am taking output voltage to be 1 volt ok. But, input voltage I am changing from 12 volt to 2 volt right. Even you can go further down. And, I am using a compensator outside compensator in typical current mode control. If you go to 2 volt and close the loop, you will get severe instability.

Not only there you know just current loop, because we know a current loop stability problem occurs at 0.5 duty ratio, but due to closed loop, thus the instability problem can be really severe. So, you need to add ramp compensation, but here we are not going to take ramp compensation.

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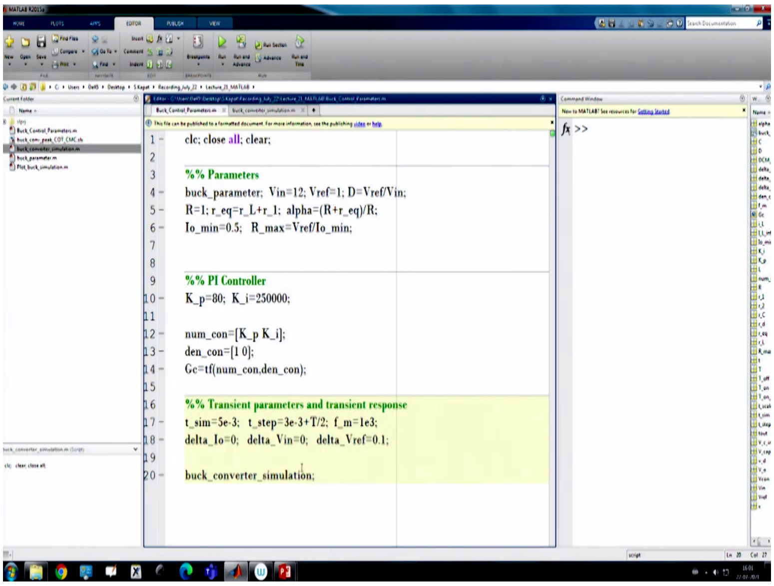

So, here I am just talking about; that means, I am changing the supply voltage. So, this control parameter I am just calling the parameter file of the buck converter, I am setting reference voltage to be 1 volt, my initial input voltage is 12 volt, and I said the load resistance to be 1 ohm.

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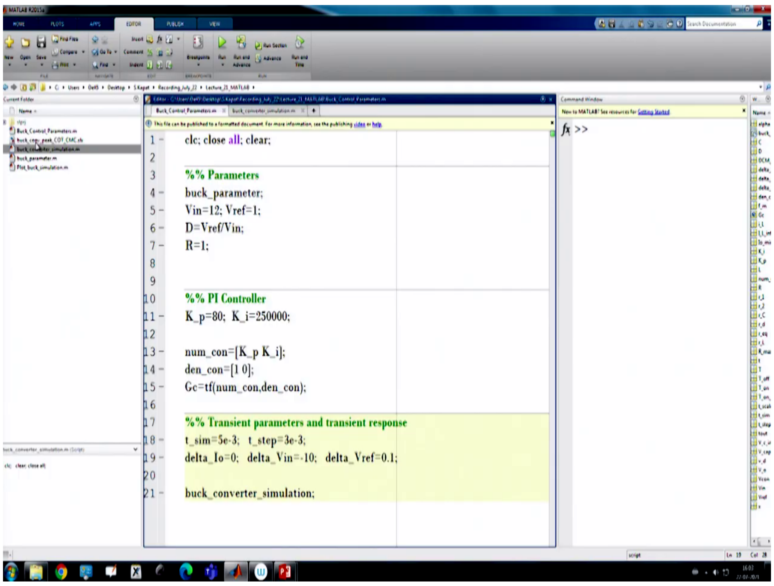

So, you can ignore all these quantities which are redundant. Even the duty ratio may not be needed. So, sorry here you need input voltage 12 volt, reference 1 volt. And, load resistance is 1 ohm, you can change it and I am setting a P I controller, where K p is 80 and K i is you know this you know 2 2.5, 0.25 into 10 to the power 6, ok.

And, then I can load this controller into the actual simulink that I will show you. And, here I am taking the total simulations time of 5 millisecond and I am applying a step transient at 3 millisecond. So, I can remove this quantity 3 millisecond. It is not needed. Now, I am applying a transient of minus 10 volts; that means, initially it is 12 volt at 3 millisecond time. I am applying a minus 10 volts step size; that means, if you go to the converter simulink diagram.

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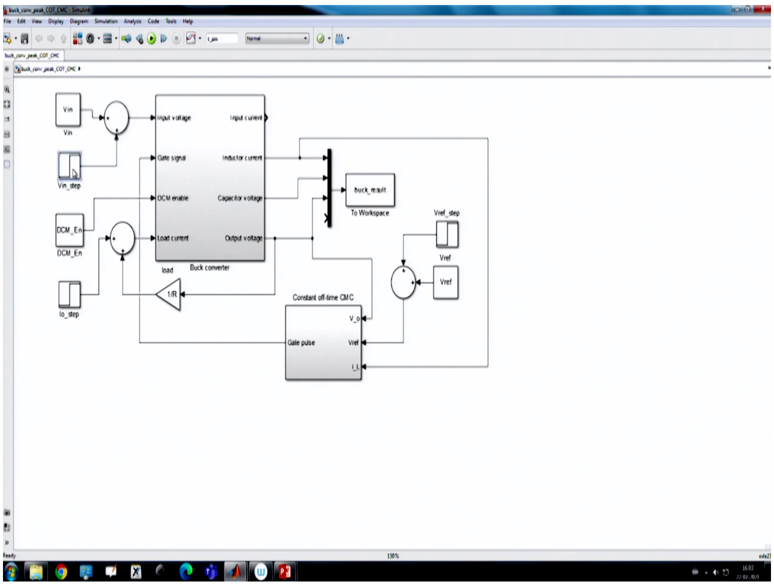

And, if we check the simulink block diagram, I will show you that in the block diagram.

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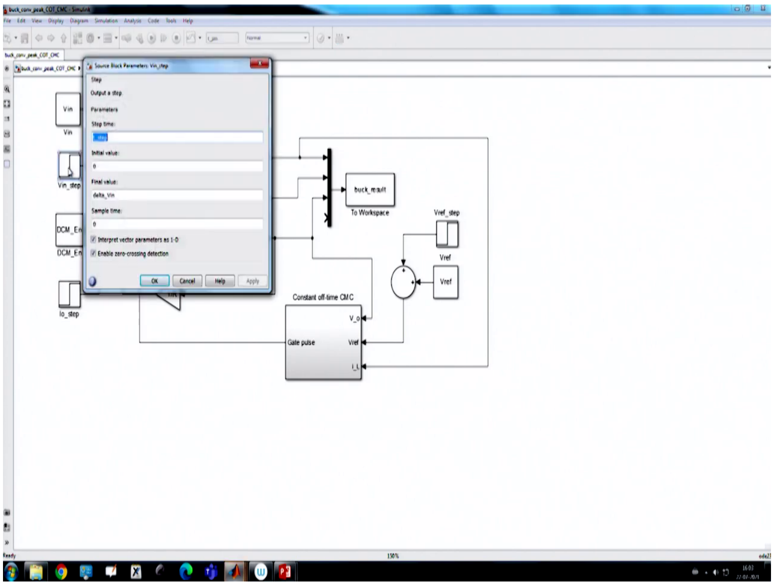

So, this is a supply state which actually we are applying with a T step and this we have discussed in the previous lectures in this block diagram.

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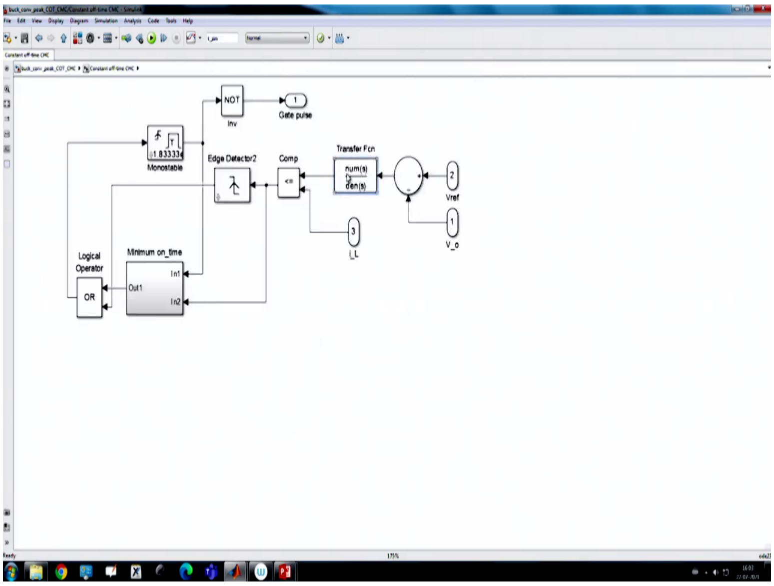

Now, if you go to constant off time. So, this controller is directly called from the bottom file ok.

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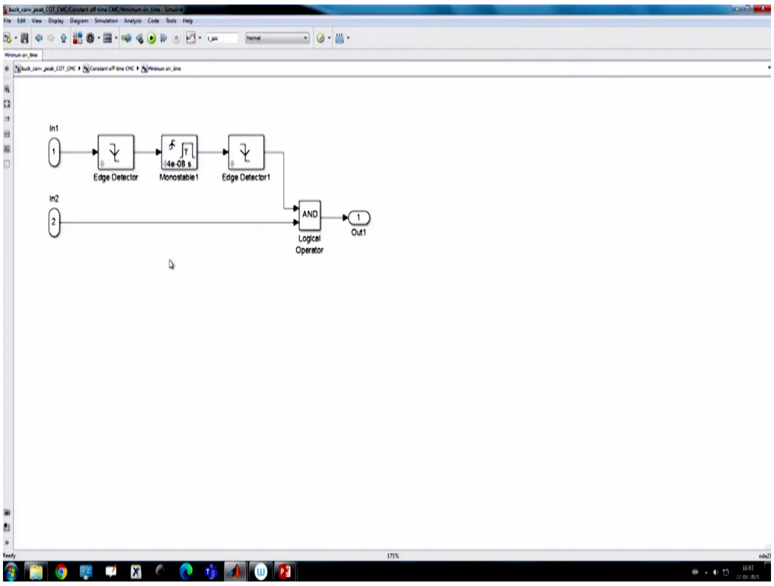

And, the on time this is the minimum on time T on minimum that we have discussed and this is the off-time. And, this on time and off-time are calculated from this file; that means, we are setting this on time is simply V ref by V in into T and off-time is T minus T on ok.

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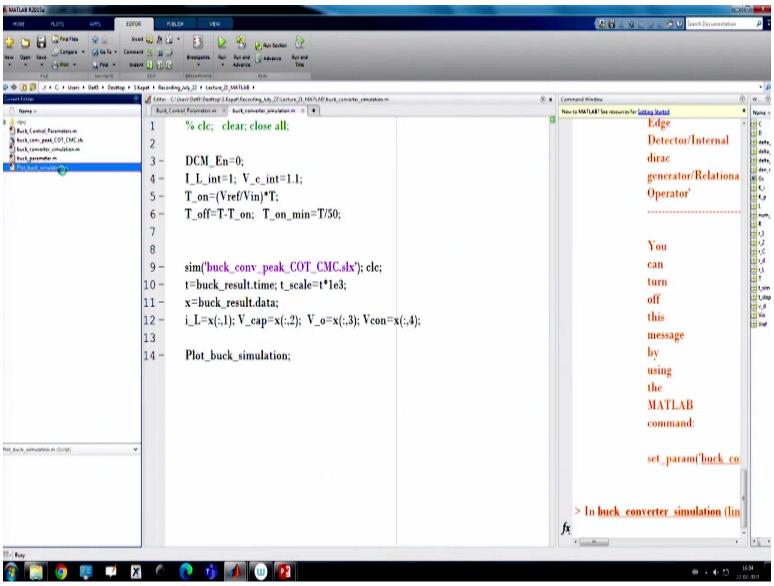

And, then we are running this simulation. So, here what I am doing? I am first running this so, loading the parameters. So, now, the parameters are loaded, now I am running the simulation. So, if I run the simulation, then if I go to the plot command, it will show the plot command, what waveform are you going to show? We are going to primarily show, the inductor current waveform and the output voltage waveform.

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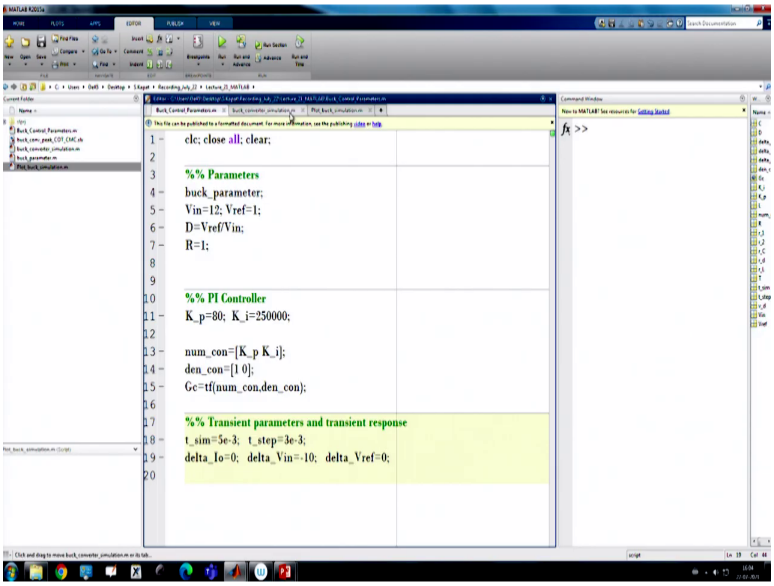

Sorry, this is the reference transient, I am sorry; I need to change ok. So, I am initially showing supply transient ok. So, let us show the supply transient, where the input voltage changes from 12 volt to 2 volt; that means, there is a change of 12 volt to 2 volt, so, very low input voltage ok.

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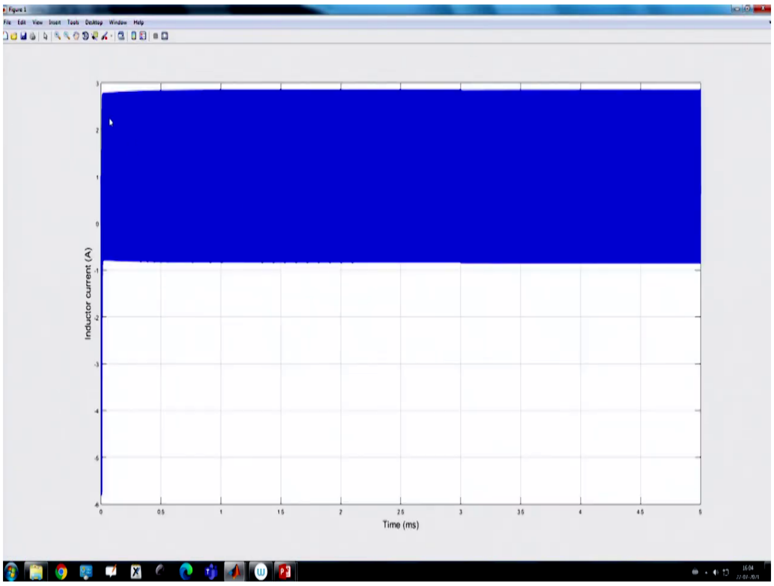

So, you will see there is no change in the inductor current. So, we have applied the supply transient here.

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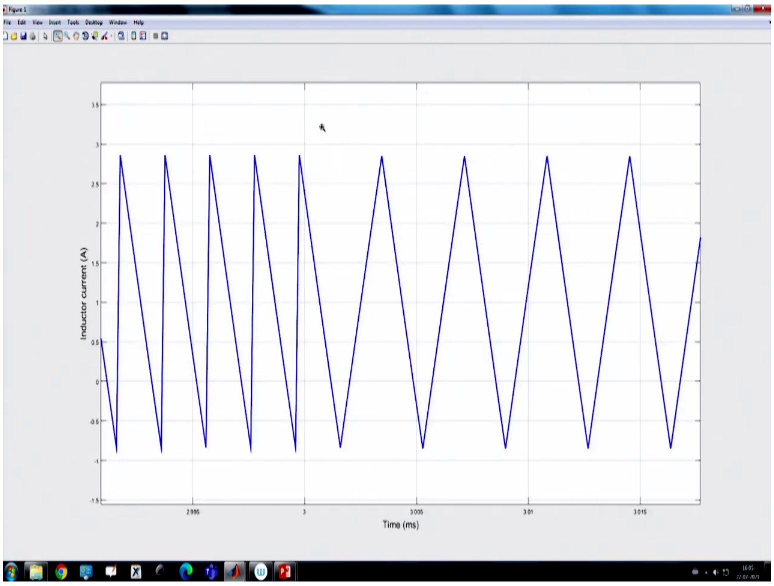

So, this is the point where applied the supply transient, if you see these are a drastic change in the switching frequency, because here we are talking about constant off-time. And, if you recall in constant off-time, we are familiar that what is the current ripple, the inductor current ripple? If, I take the falling slope it is V 0 by L into T off right.

Since we are using closed loop control so, V 0 is maintained; that means, I am getting this whole quantity is constant, this we are setting this T off which is constant. I am taking a constant value of the inductor and I am regulating the output voltage. So, this quantity is constant; that means, even if we change the supply voltage, the output inductor current ripple is not supposed to change, it will remain constant, but it will definitely change the switching frequency right and this is exactly is happening here.

So, you can see before transient this is the waveform, where your duty ratio is pretty low, you can check from here. The on time compared to the total time is low, because, if I take the cycle from here to here; it is a very low duty ratio.

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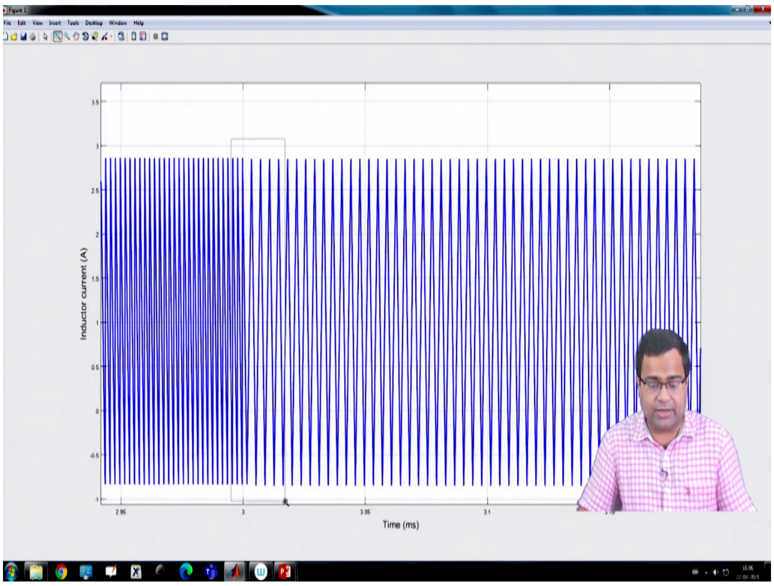

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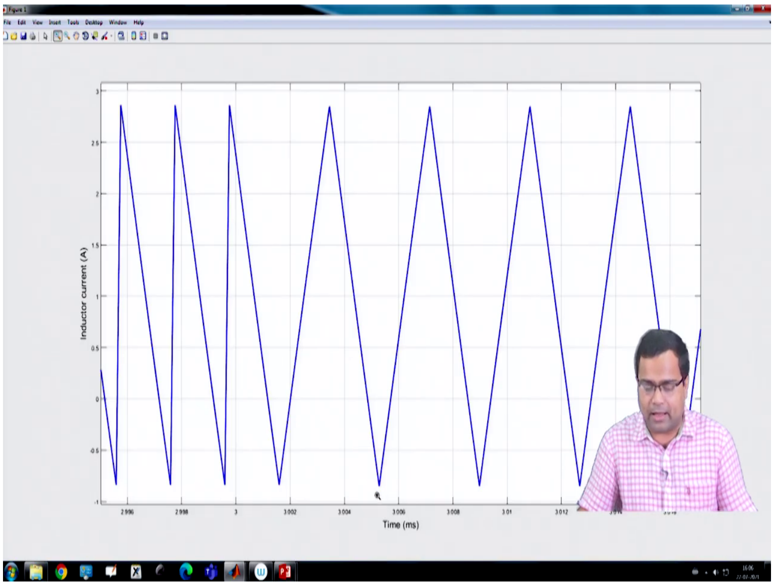

But, if you go after the transient; that means, if you go here you will find after transient if I take this the on time is pretty large compared to off-time, because here like a 50 percent duty ratio; that means, your output voltage is 1 volt and input voltage is 2 volt. So, you can further reduce there is no problem ok.

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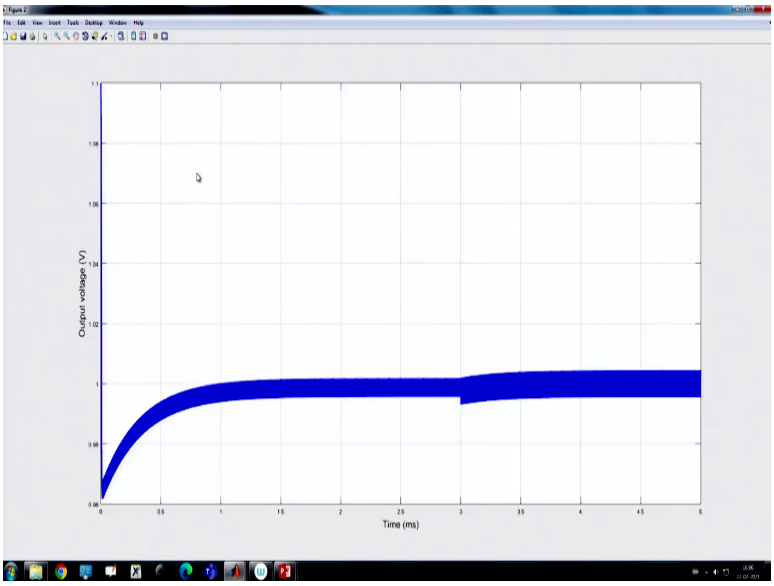

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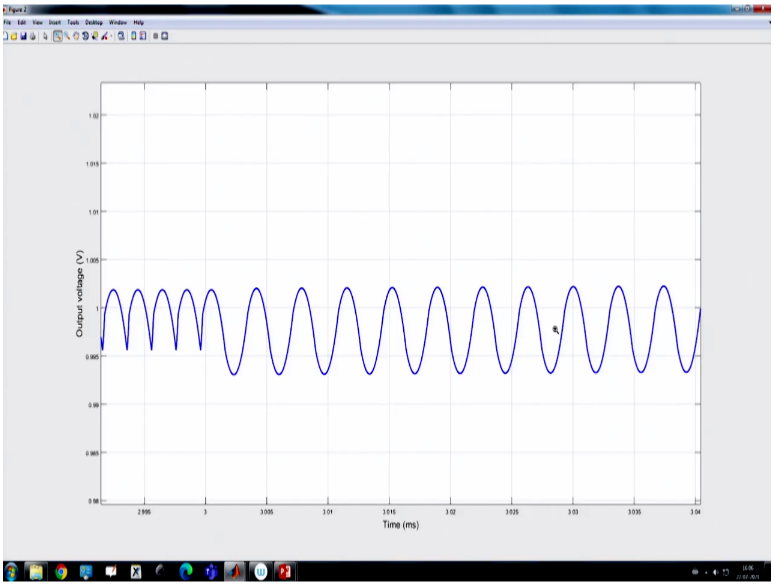

Another part I want to show, if I go to the output voltage response ok. So, if I go to the output voltage response, if you just take the few cycles. You will find there is almost insignificant change in the output voltage, because 1 volt is my output and it is more or less 1 volt, because this scale is just 0.005 5 milli volt. So, there is a like a 4 to 5 milli volt change and you can assume that there is no change in the supply voltage; that means supply remains more or less constant.

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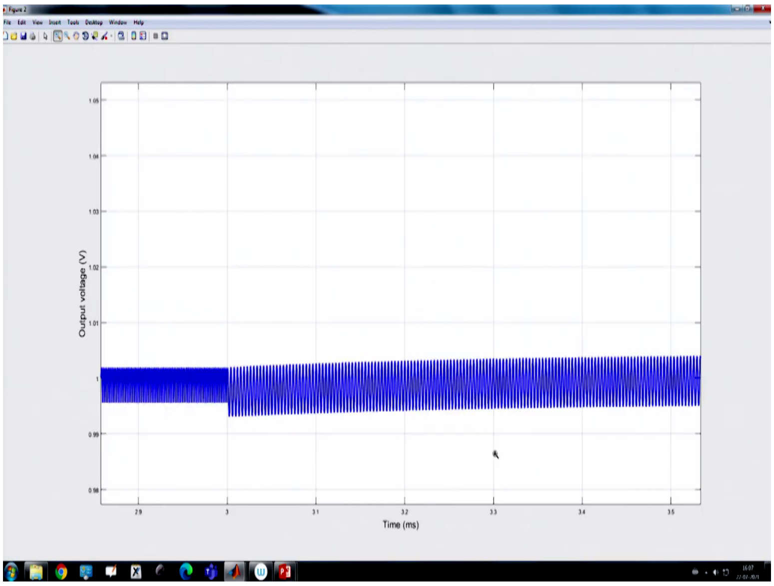

So, there is no change in the output sorry output voltage remains more or less constant, but we are we have applied a supply transient drop from 12 volt to 2 volt ok; that means this and there no ramp compensator. So, you are getting excellent supply transient performance. In fact, this is also consistent in peak current mode control, but in peak current mode control, the current loop will become unstable for this duty ratio.

And, here you are also getting superior current loop stability; there is no problem of stability. Even we are using a very high closed loop gain, it is not at all I mean it is perfectly stable. Now, we want to show we want to say load transient performance.

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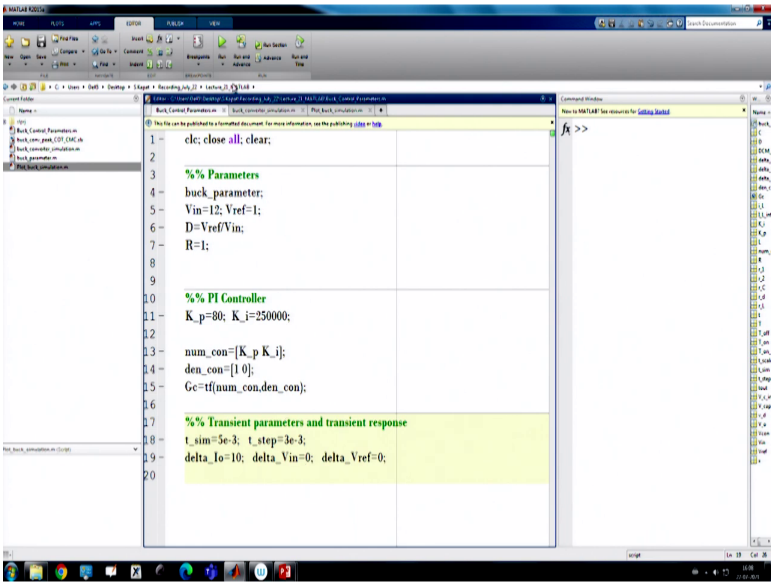

So, if you go to the load transient performance, now, what we want to do? We want to change the load from you know 10 ampere, let us say we are changing from 10 ampere. It was originally at 1 ampere load, now you are changing to from 1 ampere to ok. So, we applied a load transient and let us see. The load is changing from 1 ampere to 1 plus 10 11 ampere ok. And, we want to see that transient performance step up transient performance.

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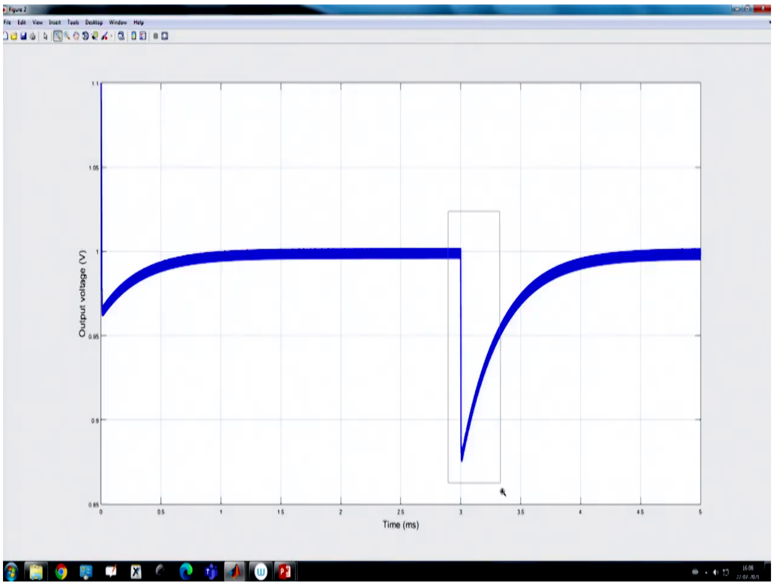

So, we need to increase the gain, because you know the current mode control is a problem, because it is a over damped system. So, we need to really increase the bandwidth in order to speed up the response ok.

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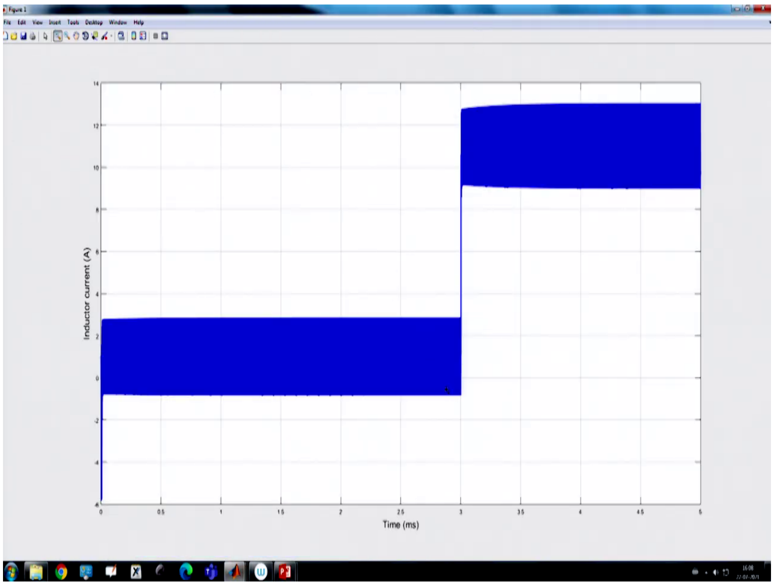

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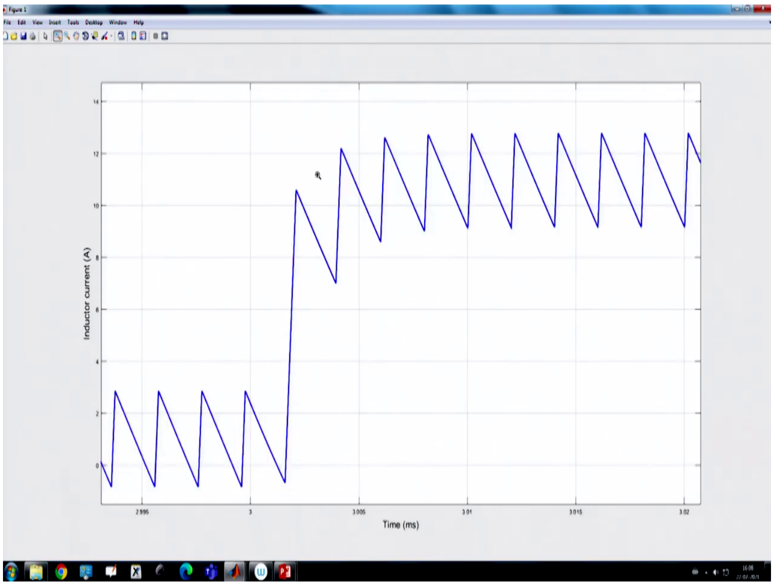

And, if you check here ok. So, it smoothly rises from this to this point right and you can also apply a 20 ampere load step so, it is not a problem. But, you see, an interesting point is that I have applied load transient at 3 milli second. When the switch was turned off and when the switch is turned off under constant off-time, the modulator will not respond to the load transient, because it will remain off throughout this interval when the monoshot timer is activated.

As a result, from 3 millisecond to you know 0.38 3.0015; that means, 1.5 microsecond; that means, the total time period we are assuming we are trying to maintain at 2 microsecond, so, almost 1.5 microsecond is a delay. As a result, you will find that the undershoot is somewhat large, because here we have applied a load step transient and since the voltage is going down. So, it is going further down ok.

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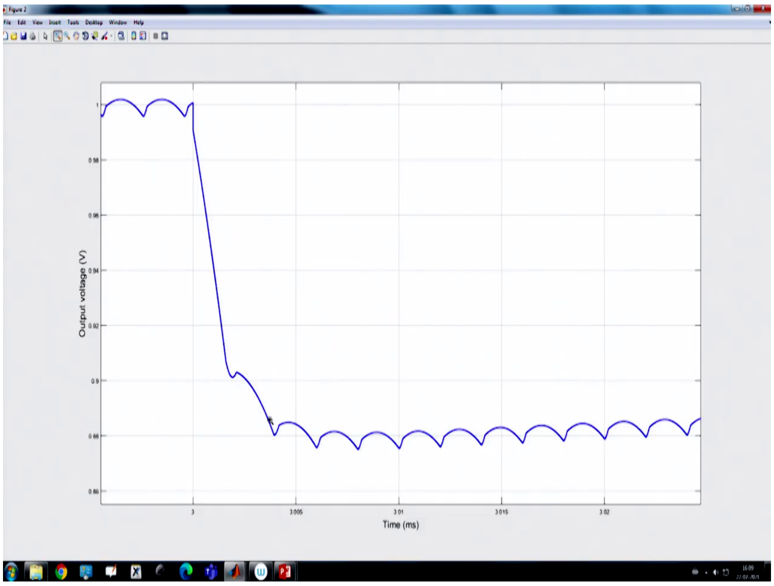

And that is why the transient response is somewhat penalized. So, if you want to consider the best-case scenario, then I want to ship the load step transient a little further right side.

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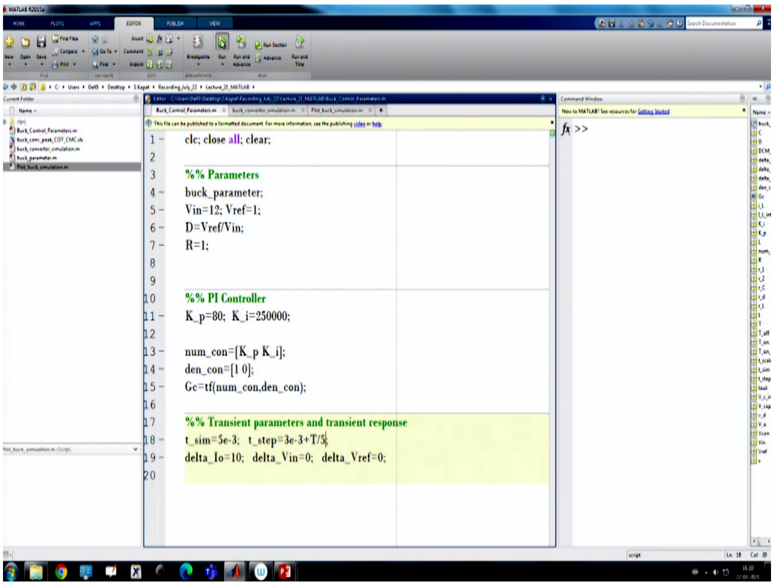

So, that it should not coincide during my off-time. And, if I do that I will just show you that if I make it a little if I shift it a little bit, then I show it the response can be improved significantly. Because a delay can cause you know further undershoot, because your constant off-time is not responding to that load transient performance, because yes.

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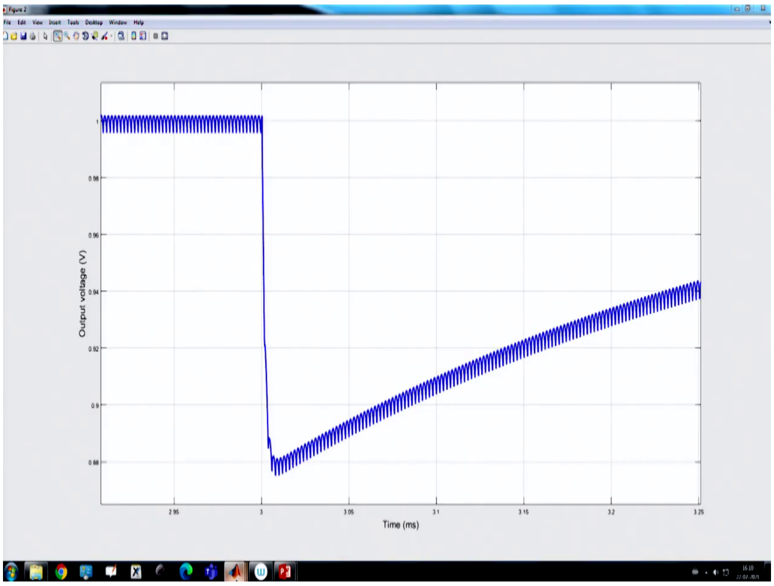

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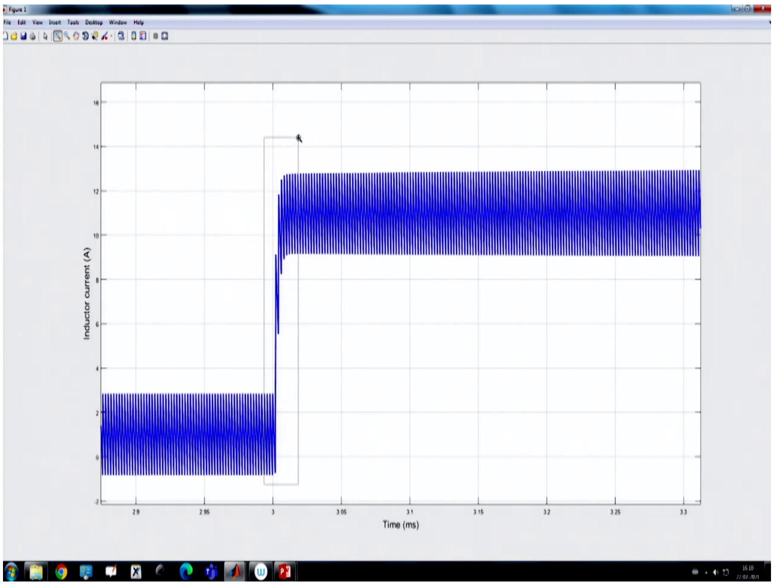

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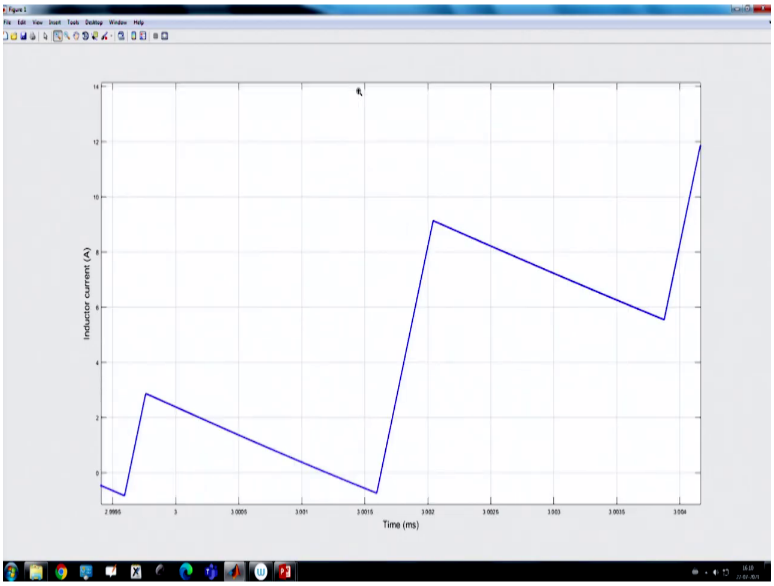

So, here if you see, if you go to the inductor current waveform, so, I want to show that the inductor current waveform here we are again we have applied load step, where did I apply? The load step we applied 3 milli second plus ok.

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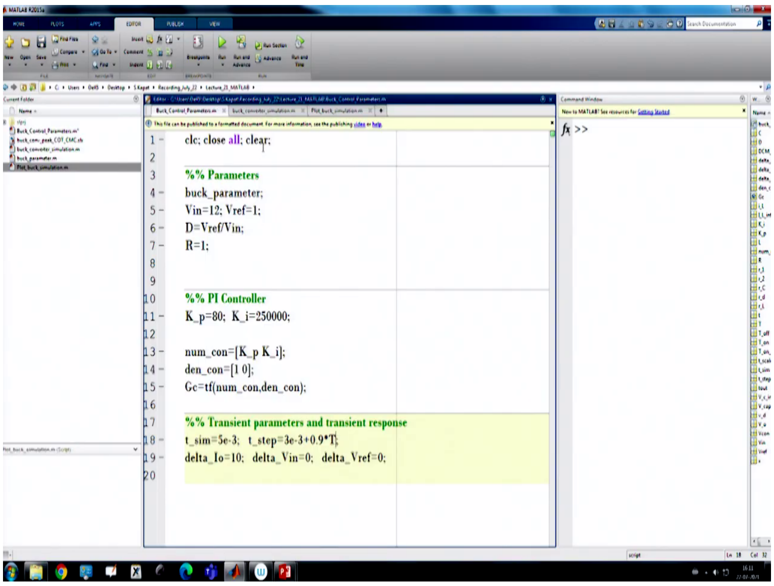

So, I need to apply a little further so that means, it should be you know T y. So, it is it should be close to T 0.9 star T. From shifting the load transient further and then; that means, it is just the adjustment. So, that every modulator whether you take you know peak current mode, valley current mode, so the modulator will have an inherent delay and if you can if the load transient yeah.

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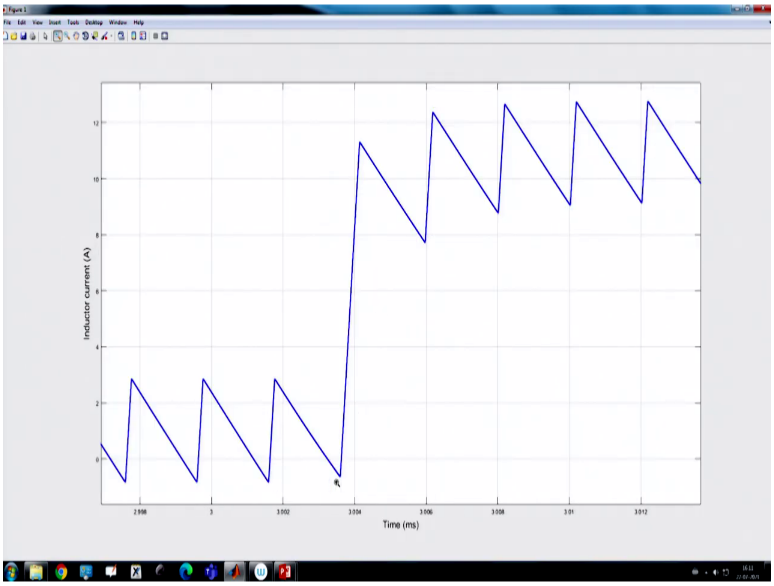

So, here we have a little bit shifted the transient response; that means, so, it is almost responding, because, a load step transient happens when we have applied the load step. If you check this point, point of transition.

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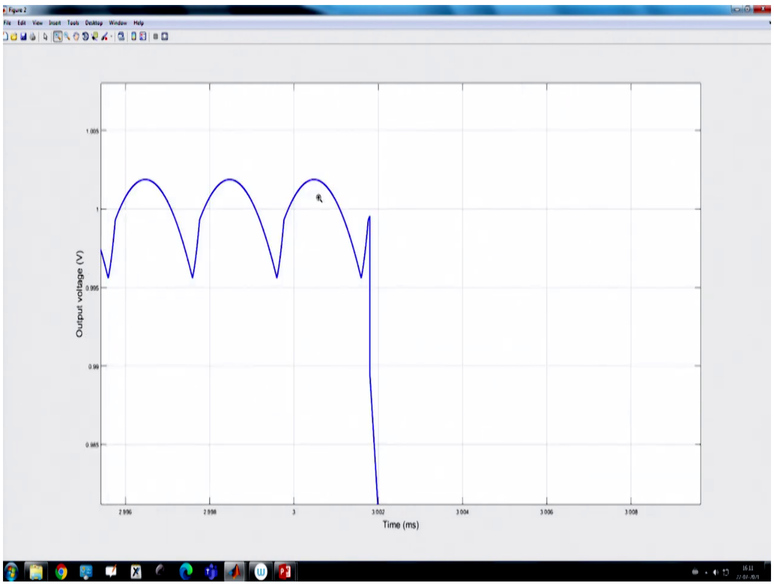

So, it is happening when the switch is about to turn on; that means it is happening around 3.0016 and if you go to this part 3.0016. So, 3.0016; that means, it is during the on time. So, this is the best possible transient scenario that you can achieve in this case, ok, but ok. So, we understood the load transient performance, the next part is a reference transient performance. So, if you go for reference transient performance.

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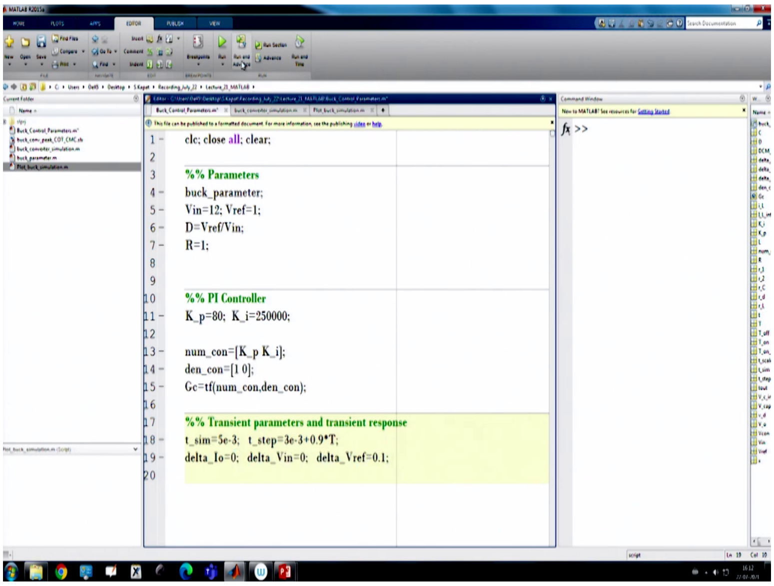

That means, now we want to apply a reference step change whereas, the load is kept the earlier load and let us run it. So, here we are applied a reference step change of 0.1 volt it is changing from 1 to 1.1 volt. So, let us see what happen, in the transient response using constant on time control.

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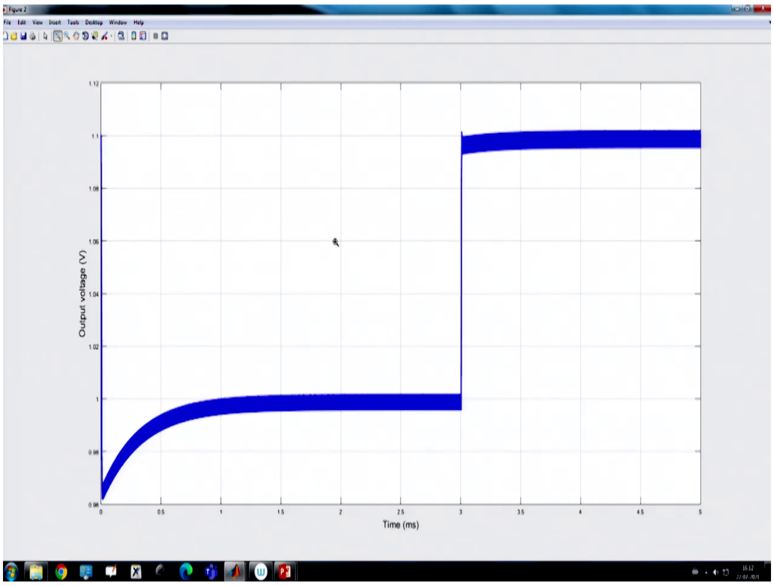

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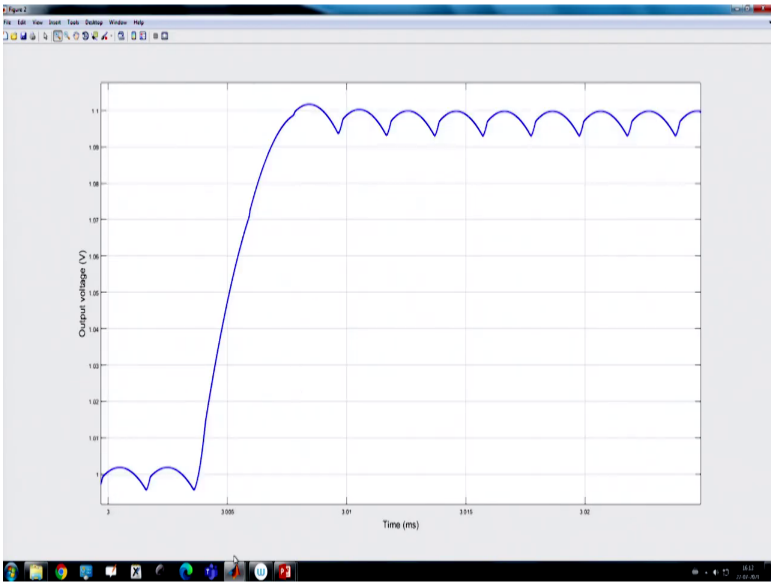

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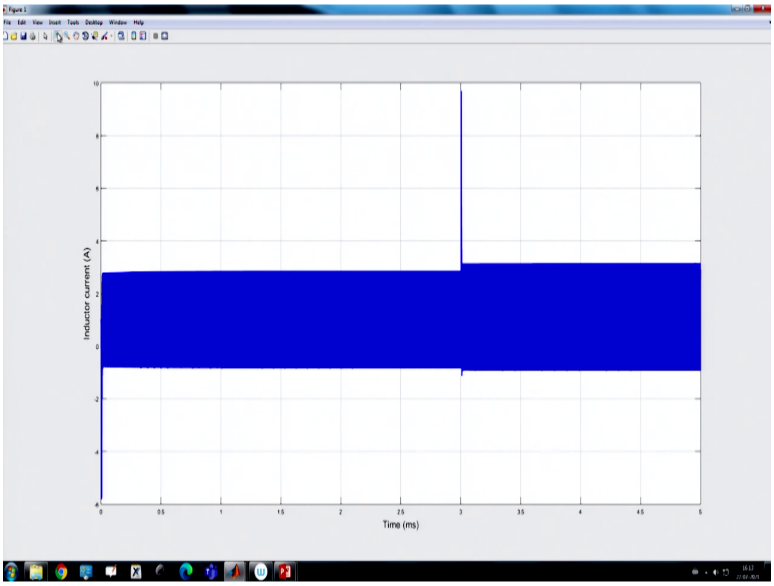

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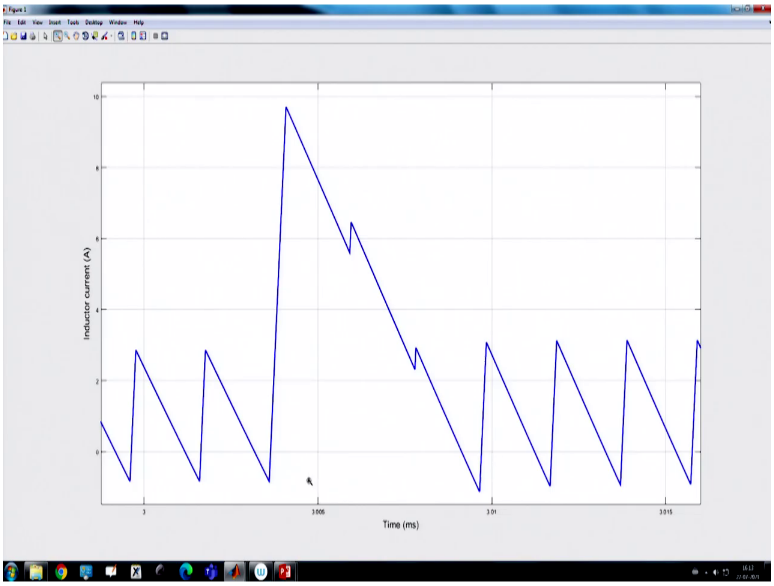

So, here you will find that output voltage reaches from one state to the other state almost in one switching cycle; that means, you know if I zoom this portion the output the inductor current slew out very rapidly and then it comes back ok. So; that means, this is somewhat close to optimal response; that means, not exactly optimal because there is a switching event here.

So, we can further improve the transient, but this is one of the very close to time optimal performance, but it is not exactly, because there is another switching event. So, by that way we can improve the step up recovery very fast ok.

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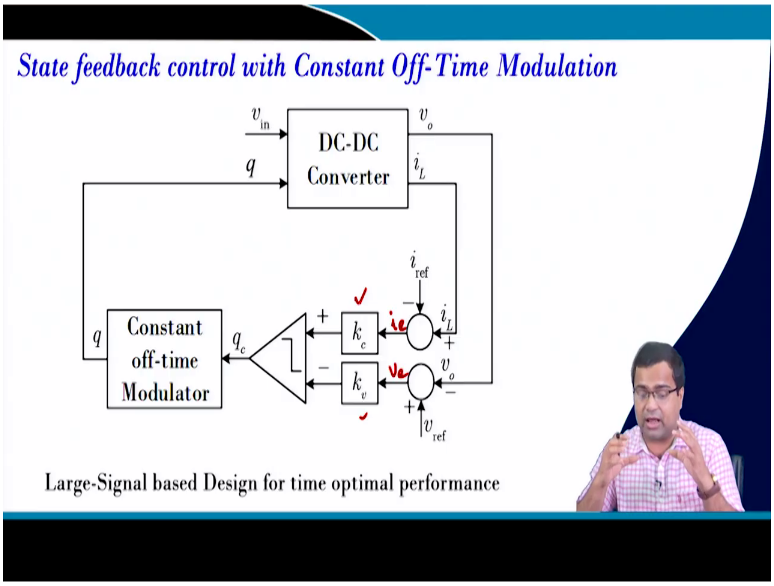

Now, we can use state feedback control we can implement using constant off-time modulator; that means, if we take i ref i L, this is my error current and this is my error voltage, then we can set the suitable current and voltage gain. And, then we can use this logic and then we can go to the modulator.

And, this can be tune we will see in subsequent lecture in the at the end, that we can even apply some sort of suitable choice of current and voltage gain, in order to obtain fastest transient response, which is a time optimal response.

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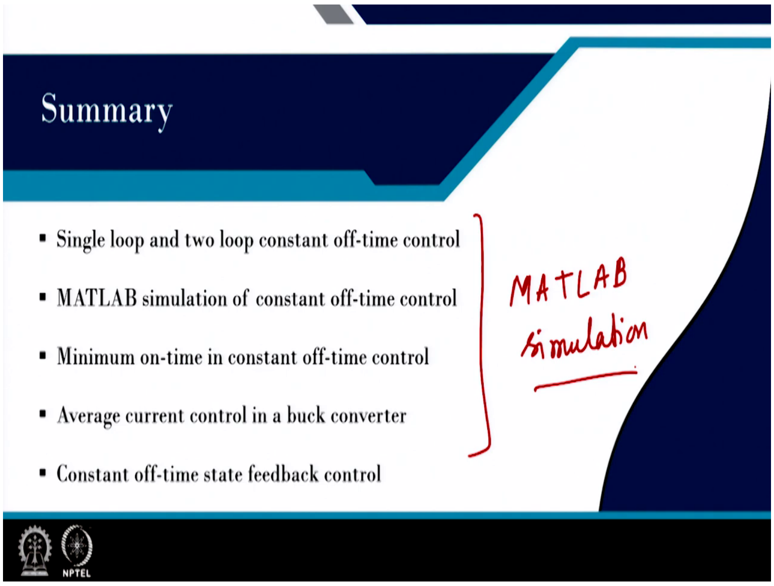

So, we have discussed single loop and two-loop constant off-time control, MATLAB simulation of constant off-time control was discussed. Then we have also discussed minimum on time in constant off-time control, then we have also discussed average current control in a buck converter. And, we have also discussed constant off-time state feedback control.

And, we have shown some performance study using MATLAB simulation that also we have demonstrated here. So, MATLAB simulation we have considered, and we have seen that the constant off-time is analogous to peak current mode control, but at the same time, there is no current loop stability issue. So, with this I want to finish it here.

Thank you very much.