Control and Tuning Methods in Switched Mode Power Converters
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Module - 04
Variable Frequency Control Methods
Lecture - 24
Light Load Control Methods and Interactive MATLAB Simulation

This is lecture number 24 in this lecture we are going to talk about Light Load Control Methods and Interactive MATLAB Simulation.

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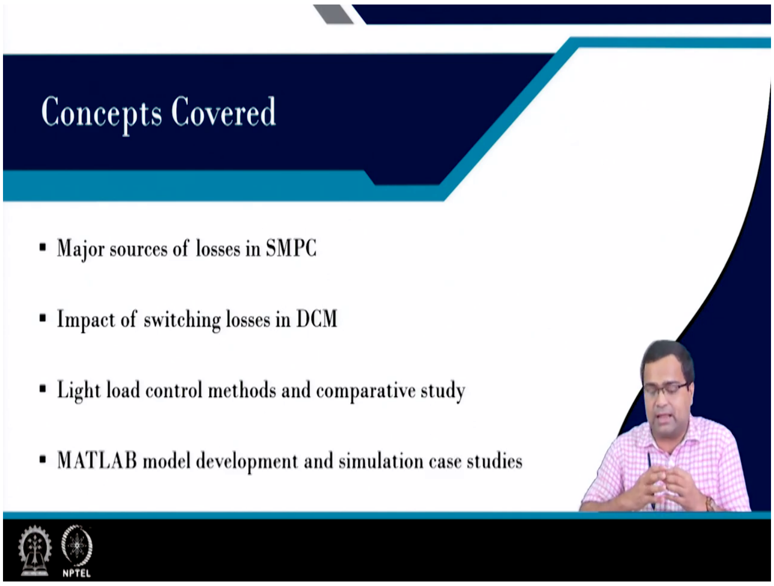

So, here we will first talk about the major sources of losses in switch mode power converter then impact of switching losses in discontinuous conduction mode, then light load control method and comparative study. And MATLAB model development and simulation case studies.

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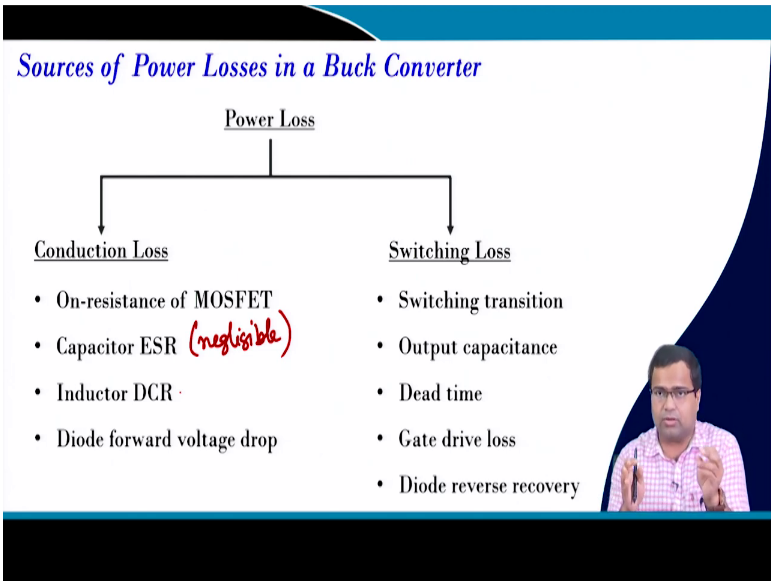

So, first we will identify what are the sources of power losses in a buck converter or any DC-DC converter it mean. So, here all the formula we are going to derive for a buck, but we can do the same thing for boost and other topologies also. So, the power loss can be divided in broadly into two category one is the conduction loss and the other is the switching loss.

Under the conduction loss, the losses due to the on state resistance of the MOSFET the ESR of the capacitor. Although this is a sort of negligible; this is negligible under high load or medium load. But this can be somewhat you know these may not be negligible when you go for very very low light load.

And if you continue to operate in continuous conduction mode, then the inductor DCR that can that due to the DC resistance of the inductor conduction loss. And if you take a diode based DC-DC converter, not the synchronous one, then the diode forward drop will also contribute to conduction loss.

Under the switching loss, we will have a switching transition loss because you know the real switches they do not turn on and off immediately. So, the switch takes some time to let us say when the switch is on, the current was flowing through the switch from drain to source.

And the so, voltage across the drain to source was almost 0, but when you turn off the switch, then the drain to voltage source drain to source voltage will slowly rise and it will reach to the voltage which is applied across the two terminals. And the current will slowly go from you know the full like a whatever it was there to zero value and that slew up and slew up and slow down process that will overlap between this nonzero current and voltage, which will lead to switching loss ok.

And if you have faster rise time, then you can reduce the switching loss. The output capacitance loss you know if we consider a MOSFET and its output capacitance means, particularly the capacitance drain to source capacitance of the MOSFET.

Because when you turn on the switch, then the MOSFET capacitor because MOSFET is drain to source voltage is 0, and the capacitor is discharged. But once the switch is off then whatever voltage appears across the drain to the source that will and the capacitor will charge to that voltage.

And again, if you want to turn on then that capacitor has to be discharged because once it is fully on then the capacitor voltage should be 0 and that energy will be lost. So, that is the lost due to the output capacitor and if we do it more frequently, then the losses in the capacitor because the energy loss actually the losses which is corresponds to the energy loss that will increase. That means, the power loss due to the capacitive loss during for fast switching will be higher.

Then dead time loss so, dead time means since if we talk about synchronous rectifier synchronous DC-DC converter we have a high side switch and low side switch. And both switches should not be turned on and off because there has to be some dead time and as I said that MOSFET takes time to you know from full voltage to full current to zero current it takes some time.

And then once the high side MOSFET is turned on then you should turn on the low side MOSFET. So that means it is like a break and make and during that time that body diode can be activated. So, if the dead time is quite large, then the body diode will be activated and that will create additional losses.

But if the time dead time is very low, then it can actually there can be a scenario when both the switches will be on and the supply can be shorted to the ground and it will actually result in a high shoot through current. So, you have to consider the dead time very carefully, then the gate drive loss.

So if you increase the switching frequency, the gate capacitance of the MOSFET need to turn on rapidly. Then you need to provide initially high spike current in order to charge the gate capacitance and then create the channel and that faster you know turning on and off the MOSFET.

And if we use a high current gate drive circuit, then the drive a loss can be significant. I mean, that is a function of switching frequency. And of course, the diode reverse recovery loss if you take either you take a body diode or you take a conventional diode base, you know DC-DC converter.

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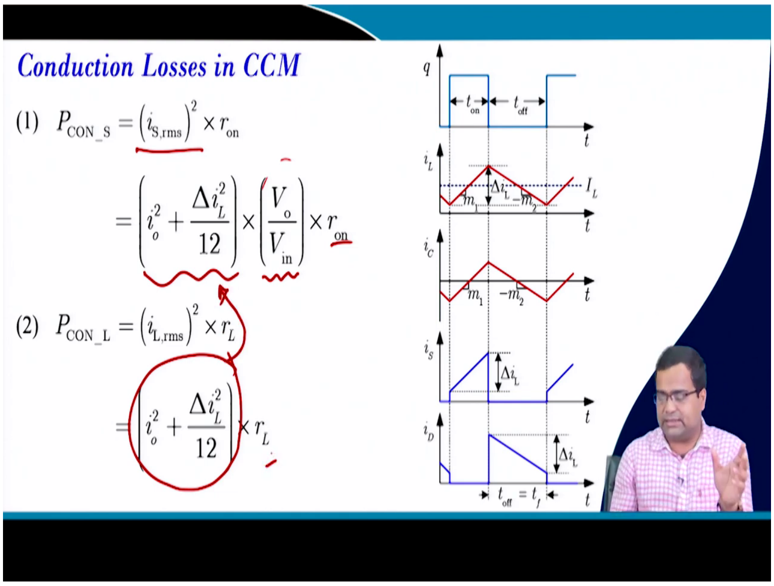

So, in conduction loss, if I take continuous conduction modes, it can be written as i S rms current if you talk about the conduction loss of the switch into r on. And we have actually discussed in lecture number 7 how to derive rms current for any waveform, which takes the form of a piecewise linear waveform right, that you can very easily find the rms current.

So, the expression of this rms current this expression we will see that this is an expression of the rms square of the inductor current, that multiplied by on time D that is a duty ratio the portion of the time when the high side switch is on into is r on. So, that means the switch rms current square is nothing but inductor rms current square into duty ratio. If you take the inductor rms current square, this is exactly I told this expression is here ok into r L which is the DCR.

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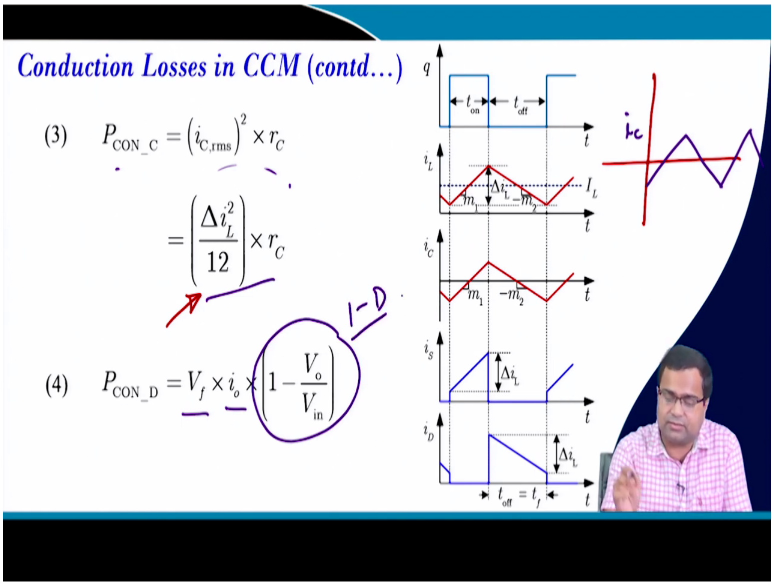

Then if you take the conduction loss of the capacitor ESR, so, capacitor average current is 0. So, it only has a ripple current and then its rms value will be simply delta i L square by 2 by 12; delta i L square by 12. And that into r C will be the conduction loss due to the ESR.

Now, when you are talking about very light load condition because there are scenarios you know if you talk about LED driving dimmable LED that particularly if you are talking about you know the PWM dimming then the LED string will be connected and disconnected.

So, once it is disconnected, suppose a buck converter is driving a LED, then the output current of the buck converter is 0. And if the output current of the buck converter is 0 and if it is running under synchronous conduction mode; that means, if I talk about a scenario where this is my capacitor current and the capacitor current will be same as inductor current if the load is removed in a synchronous.

That means the power will back and forth. It will flow between the source and the load, sorry because there is no load. So, the capacitor will actually re circulate the energy through the source, ok. But, if we take a diode base implementation, then this problem this will be a problematic because the diode will not allow negative current and you have to be very careful about the closed loop control.

Otherwise, your output voltage can drastically increase and it can go set to the input voltage ok. So, you have to be very careful. So, under synchronous configuration, the law says if you continue to operate the converter in CCM mode as I said in PWM dimming you want to turn on and off the LED very fast.

So, you may need to operate CCM continuously. In that case, this loss may not be very low when you are talking about almost no load condition. Otherwise, for a nominal condition the capacitor ESR loss is negligible.

The conduction loss due to the forward voltage drop; that means, if you take a diode base architecture, then the forward voltage into the average current during the off time, which is same as the inductor current. The average inductor current is same as the load current. And this diode will conduct during 1 minus D. So, this corresponds to 1 minus D, ok.

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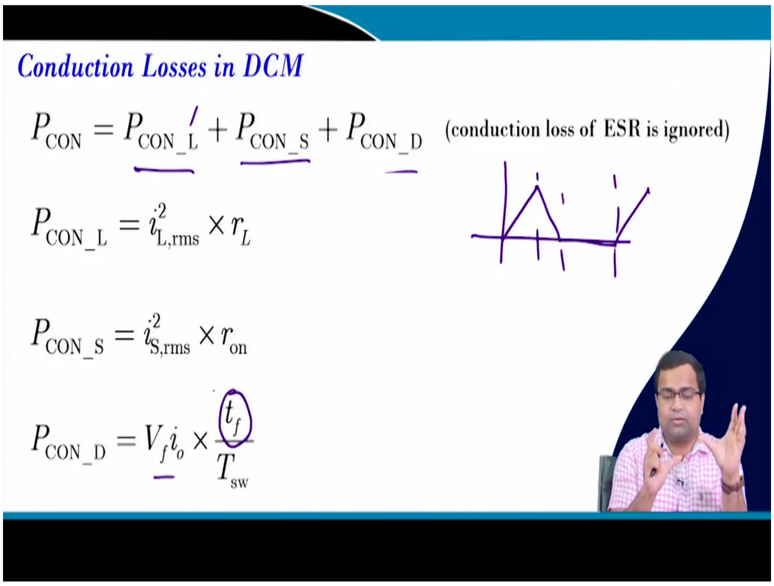

But, if you take discontinuous conduction mode, so we will have conduction loss of the inductor current conduction loss of the switch and the conduction loss of the diode, but here the ESR loss is negligible. Next, if you take the conduction loss of the switch inductor current then again you can draw the inductor current waveform and we have discuss earlier; that means, this is the inductor current waveform, right.

So, and this has a piecewise linear approximation since we divide into sector and then you obtain the rms current. Similarly you can obtain the switch current and you can also find out the conduction loss of the diode because the diode is also turning on and off ok. But here you know this is the time when the diode is you know activated that is a during the off time.

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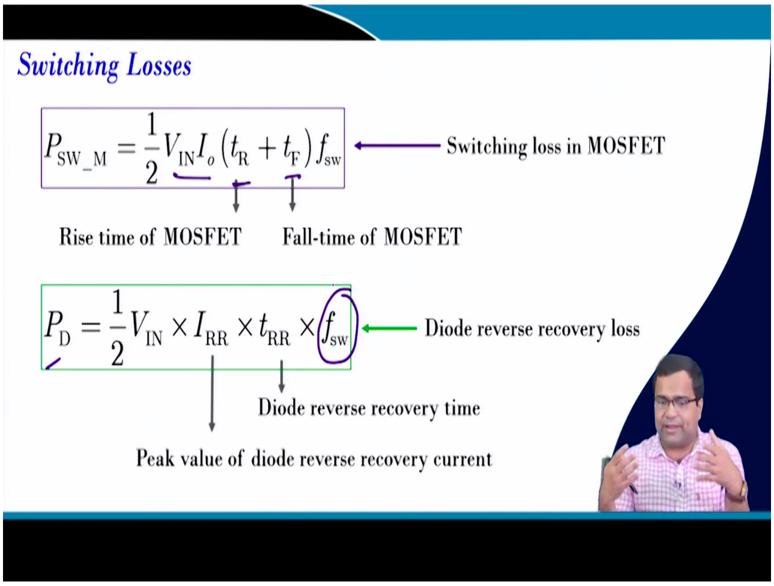

Switching loss: If we take the main switch the switching loss is the that switching transition loss can be written like this and where, t R and t F are the rising and the falling slope of the MOSFET. So, I am not going because these are very standard and you can go to any data sheet or application note you will get all this formula. Then the driver loss sorry diode reverse recovery loss which corresponds to the input voltage and reverse recovery current and the reverse recovery time ok.

So, if the diode has a larger reverse recovery time then the more losses will be there ok, but it depends on the switching frequency; that means, how often you turn on and off this diode. So, the reverse recovery process will happen you know more frequently if you increase the switching frequency for a given interval of time.

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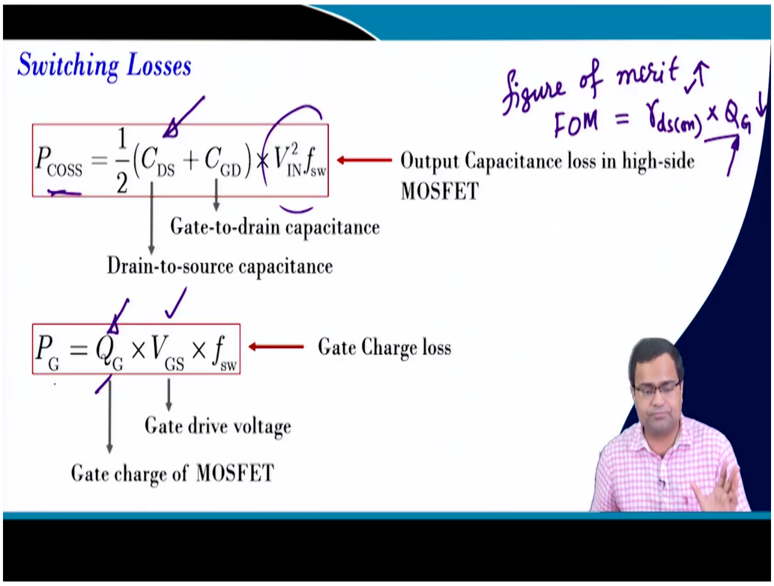

Similarly, if you take the output capacitance loss so, this output capacitance loss primarily decided by the drain to source capacitors ok. Because this capacitance will be charged to the voltage across the V DS when the switch is off and it has to be discharge when the switch is on. And that energy will be lost and that can be computed and you know energy by time is the power. So, this is the power associated with the in the output capacitor loss.

Then the gate drive loss. So, gate drive is the Q G; that means, the total gate charge requirement and it depends on this Q G can be very low so; that means, a very high; that means, if you take a MOSFET. And we know the figure of merit figure of merit figure of merit FOM typically this is r ds on into Q G; that means, if you select a MOSFET with higher r ds on then Q G can be reduced and if you select a MOSFET with lower Q G then rds on will increase ok.

And this is particularly important because if you go for very high switching frequency then you need to reduce the Q G. But at the same time if you want to operate the MOSFET for a higher current then the conduction loss the r ds on be high because you are reducing Q G. So, r ds on will go up if you want to reduce Q G and if you operate this MOSFET for a higher current application then this r ds on will contribute to a significant increase in the conduction loss.

So, this FOM figure of merit is that is the tradeoff between the conduction loss and the switching loss and it is associated with the driver loss. So; that means, if you can reduce the Q G you can reduce the driver loss, but for a given Q G and given gate to source voltage then your switching frequency how often you are turning on and off switch. So, gate drive loss will be associated with that.

And we will see this gate drive loss, switching loss these are the major problem when you operate pulse width modulation, when you operate a DC-DC converter under discontinuous conduction mode using a pulse width modulation ok.

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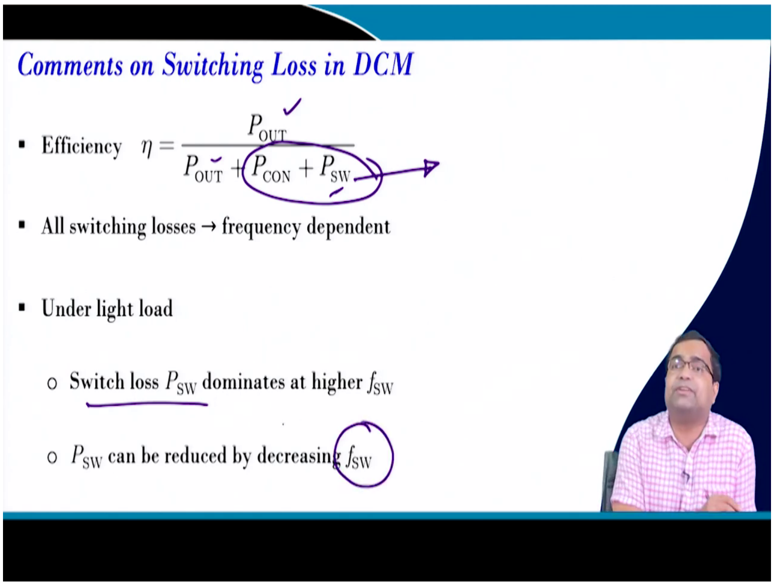

So, comments on switching loss if you take the efficiency of the converter it is the output power divided by output power by losses plus losses so; that means, the total power. But, now if we go so, all switching losses we saw it is a frequency dependent and if you the power level is very low; that means, if we take a portable device where, most of the time it under you know it is either in standby mode or very light load condition when the output power requirement is very very low.

But, if you cannot reduce the switching loss because you are turning on and off the MOSFET at a very fast rate 10 megahertz switching frequency. Then the losses of this due to the switching can be comparable in some cases it can be higher than the output power particularly, under very light load condition when the efficiency can degrade significantly. And it can be in the order of some 10 percent or 20 percent like that.

So, the switching loss is dominated by you know the under light load condition the switching loss dominate. Then switching loss can be reduced by reducing the switching frequency and that is the motivation for going for light load control.

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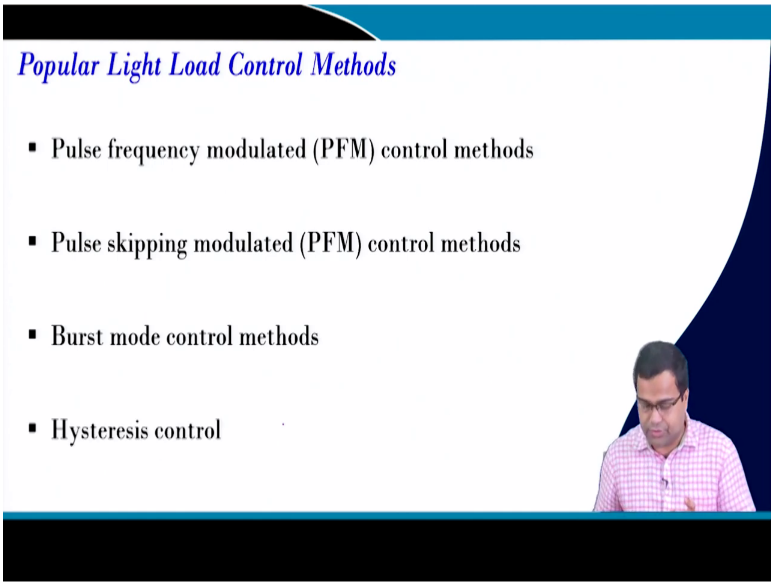

So, the popular light load control using pulse frequency modulation technique, pulse skipping modulation technique, burst mode control and then hysteresis control.

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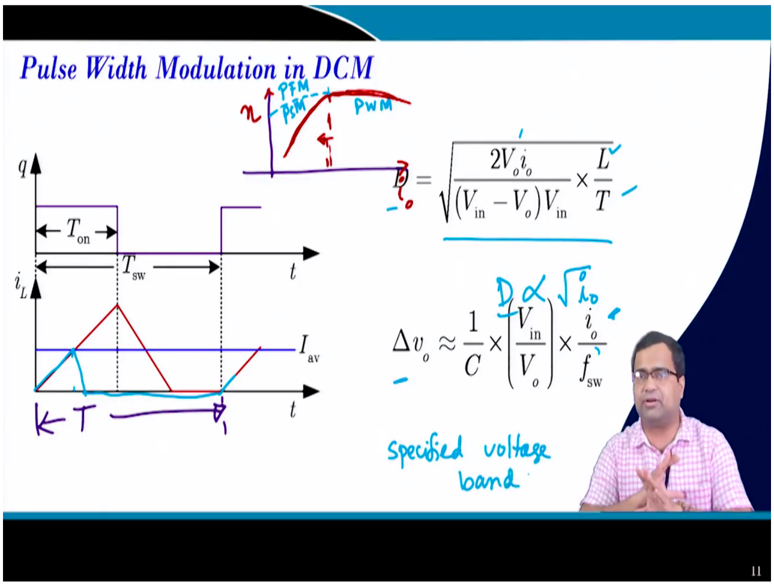

So, we will take one by one in pulse width modulation we know that this is pulse width modulation and we want to avoid this pulse width modulation under very light load. Because if we maintain this time period throughout high load and light load and which is designed reasonably high switching frequency then your switching loss can be significantly high and efficiency will fall drastically ok.

And in fact, if you go through any product datasheet and if you draw the tentative suppose, this is your nominal current I mean not nominal, nominal current can be high. So, you will find generally the efficiency curve like this and here it falls drastically this side. That means at some point you will get some optimal efficiency, but if you increase this is with load current variation and this is the efficiency plot.

So, if we increase the load current then slightly it will decrease because our higher load current your conduction loss increases. But if you decrease the load current and if you maintain the pulse width modulation your switching loss dominate and your efficiency can fall drastically and that is this is something not acceptable.

So, you know in most of the commercial product they extend it by means of PFM. So, they operate you know PFM or sometimes pulse skipping modulation, but this time it is operated in PWM. So, there is a multimode scheme; that means, two control techniques are merged together.

So, if you take the discontinuous conduction mode under pulse width modulation we have already seen that duty ratio is a function of load current and all; that means, if L T output voltage input voltage everything is constant then duty ratio is directly proportional to square root of i 0. That means, if the load current decreases the duty ratio decreases and if the duty ratio decreases this will become smaller and smaller ok.

That means, it is not necessary to operate at a high switching frequency because your duty ratio is become very low. And in output voltage is proportionally varies with the load current if your switching frequency is constant, but why do we need to reduce the output voltage? Because your output voltage has some specified band right some specified voltage band will be given to you as long as you can maintain the output voltage within the band then you are safe.

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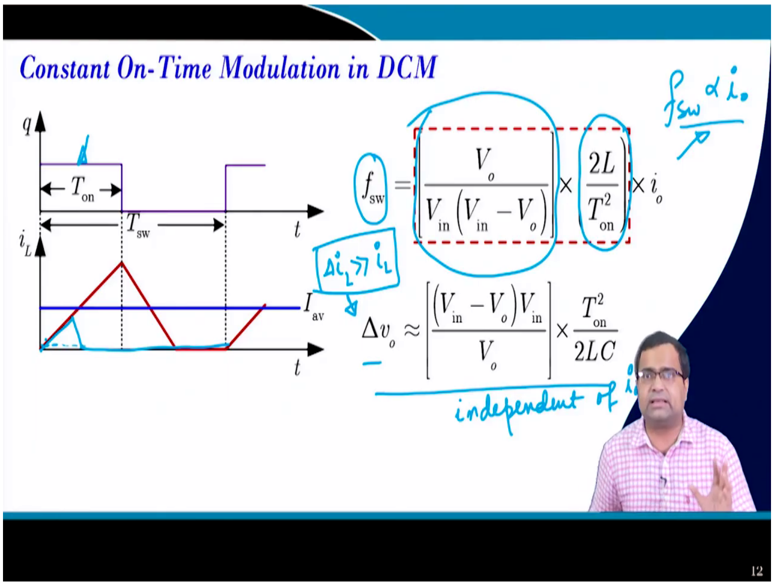

So, constant on time control if you take where, the on-time is constant and the time period will vary. And you can we already we have seen the switching frequency under constant on time control can be written like this where, if you keep the input output voltage constant. If your on time is already fixed an inductor is fixed then switching frequency is actually linearly proportional to load current.

That means if the load current decreases your switching frequency decreases as a result your switching loss decreases and this technique is very popular in commercial product where they move to PFM when you go to light load operation. Another interesting thing if you take the output voltage ripple.

Because in this case as you go more and more light load condition, it can be shown that the average inductor current is very low so, the your current ripple can be very very larger than the average inductor current. If this is true then, output voltage can be approximated like this.

And you see the output voltage under constant on time control is independent of load current; it is independent of load current. That means, under light load condition if you maintain the constant on time you are getting the benefit of high efficiency by reducing switching frequency when the load current decreases. At the same time you are keeping the voltage ripple within the band because the voltage ripple is not changing ok. And we will see this in simulations case study.

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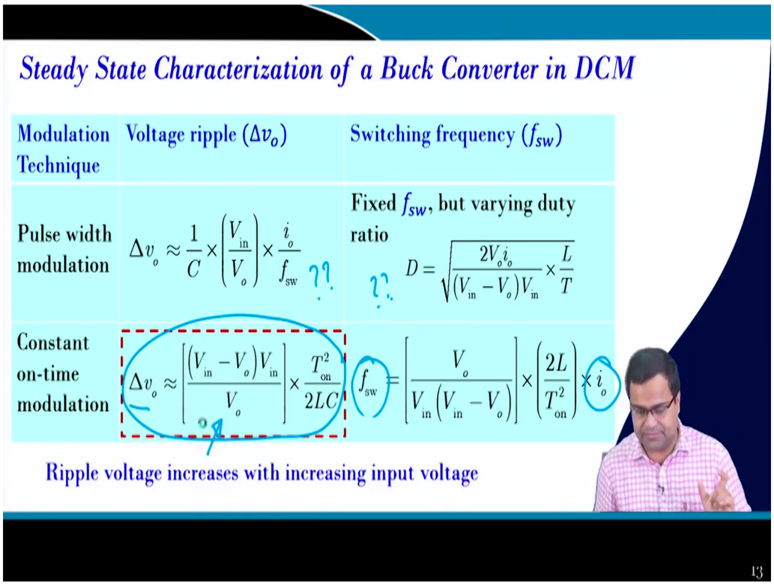

So, the steady state characteristic, if you take a constant on time control and the pulse width modulation the output voltage is more or less independent of load current and switching frequency varies proportionally with the load current. And you have a real problem in PWM under light load when your switching losses are high, but this quantity if you see it is input voltage dependent. So, suddenly if your input voltage increases then your ripple can be drastically affected ok.

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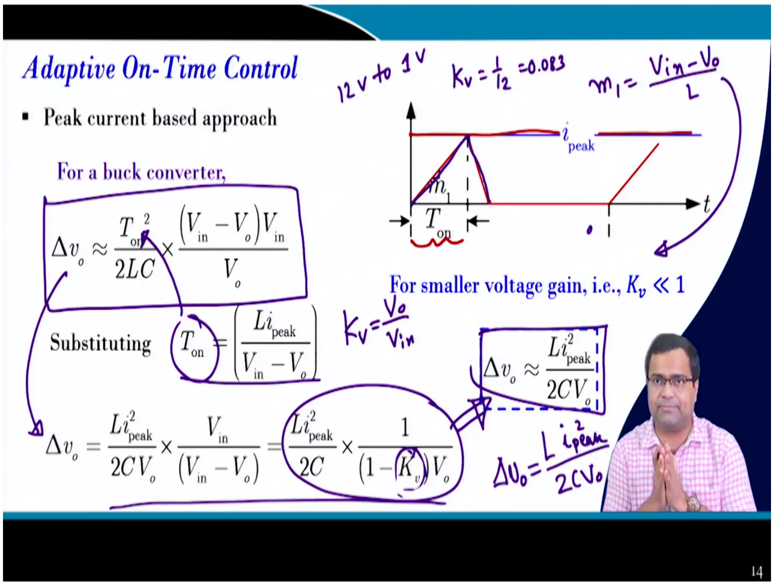

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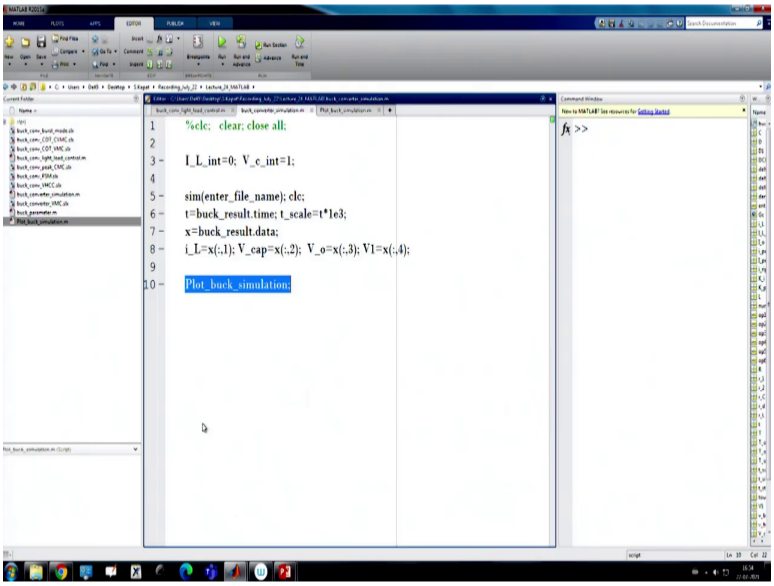

So, we will see in case of you know if you go to MATLAB case study. So, I want to show you.

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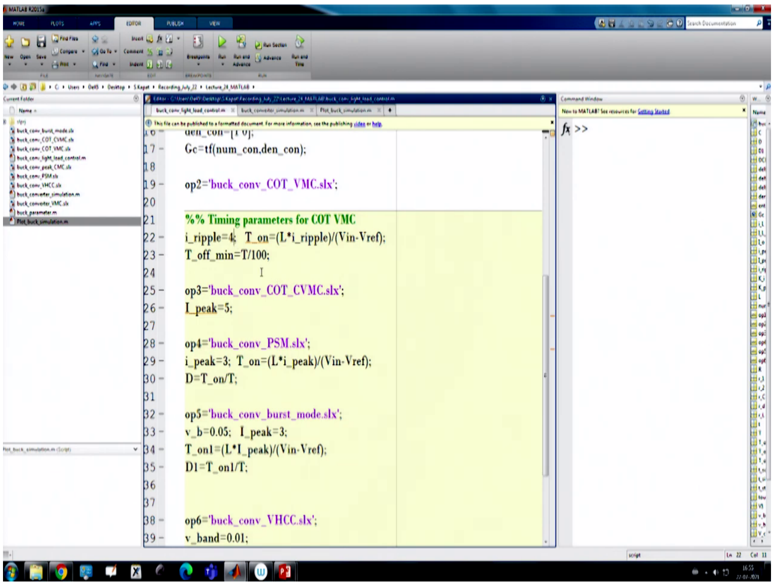

I mean I will go to the actual one minute. So, I will go to the actual case study, but I want to show that if this is the constant on time control under light load control.

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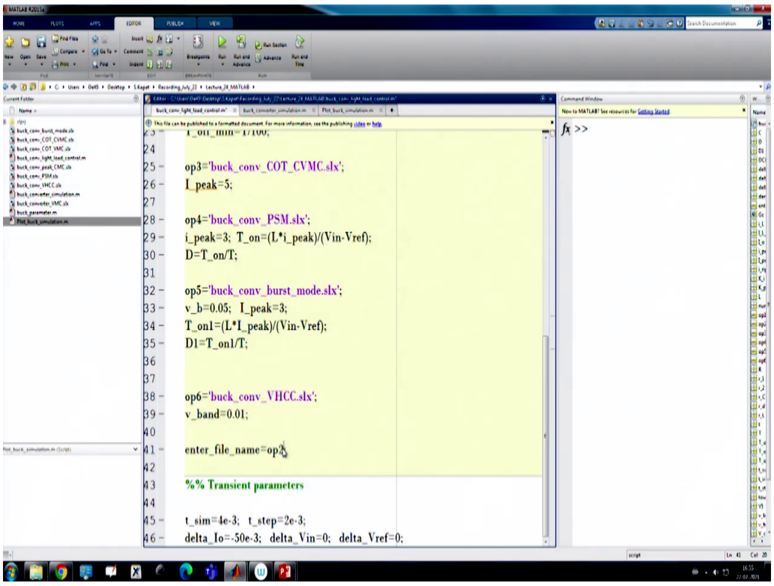

So, this is the constant on time I am trying to now this is our option 2 constant on time control and operating constant on time control.

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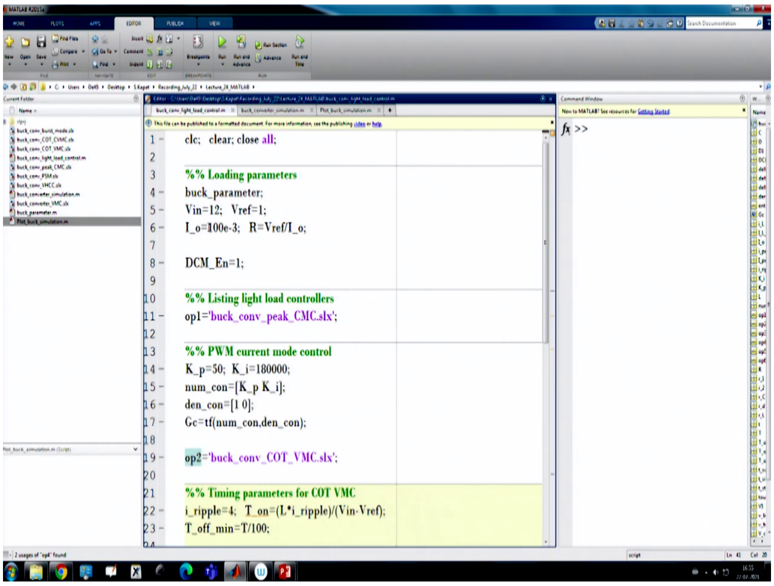

Now, I am applying a load transient it is initially at 100 milli ampere then changing from 50 milli ampere and I want to run this simulation and check what happen.

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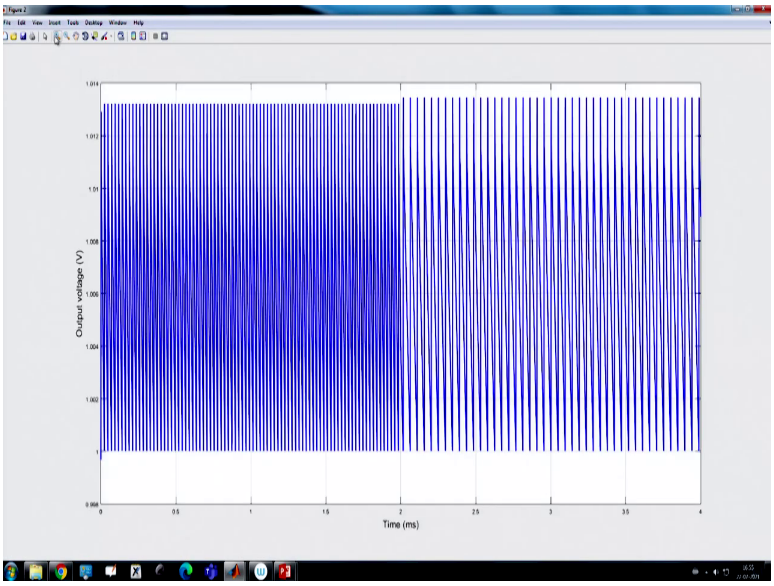

So, this is I am running with constant on time control and you will see this; that means, before 2 millisecond and after 2 millisecond.

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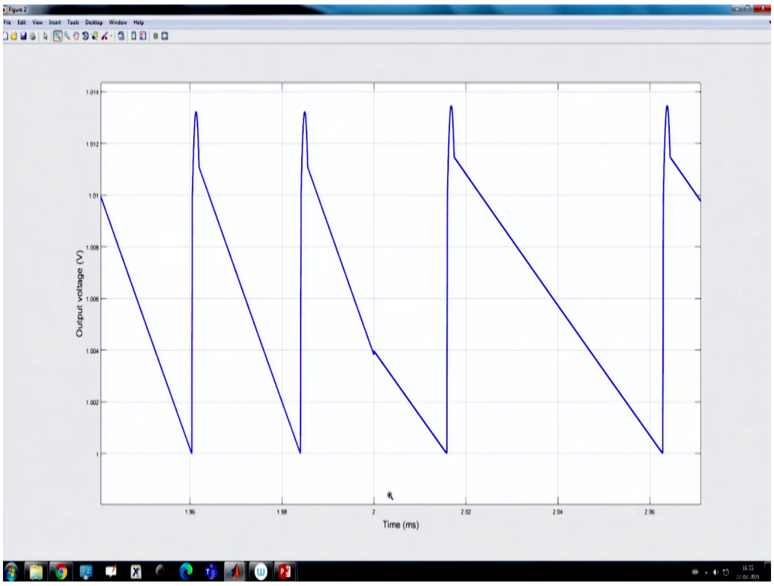

So, before 2 millisecond the load current was 100 milli ampere and after 2 milliseconds the load current becomes 50 milli ampere. And you can see the time period here is and time period here. So, here time period is double compared to this. That means your switching frequency become half and you will see the output voltage ripple is more or less constant and what we have discuss.

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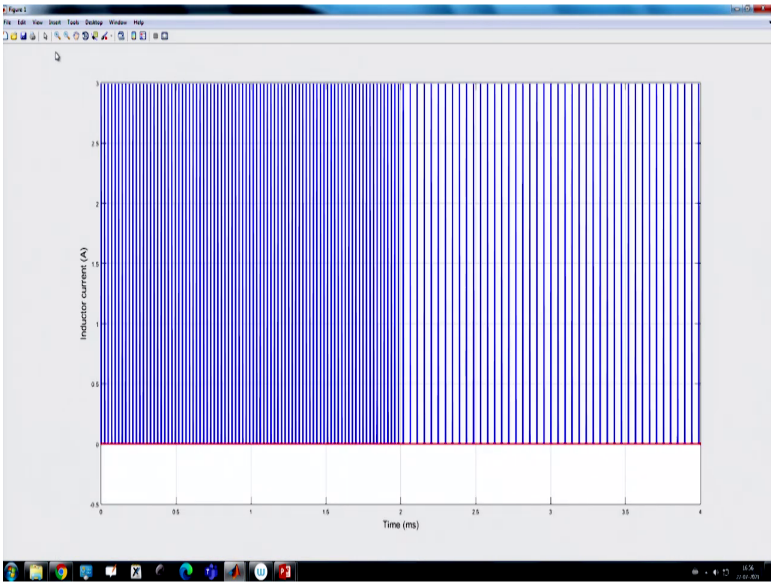

And if you go to the inductor current waveform you will find the inductor current if I maintain the peak reference current. So, it is perfectly fine.

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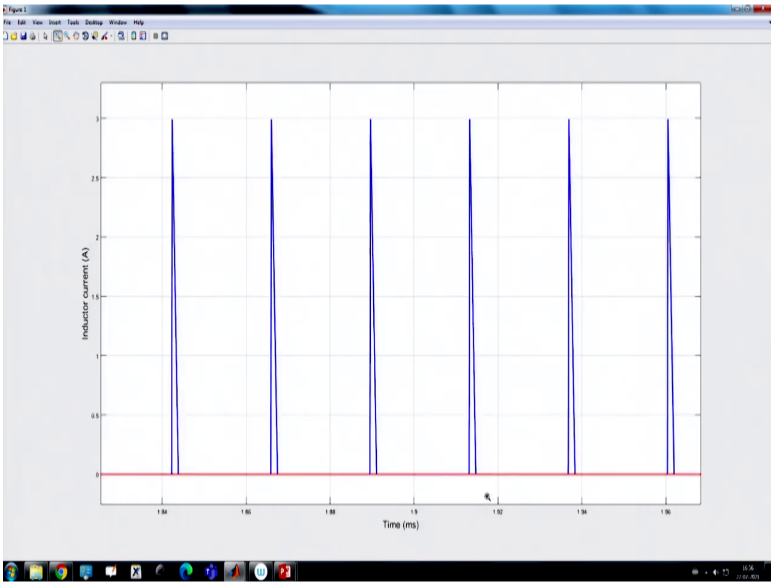

This is my inductor current reference ok. So, whether you go before 2 and after 2 the current remains same because your on time is fixed.

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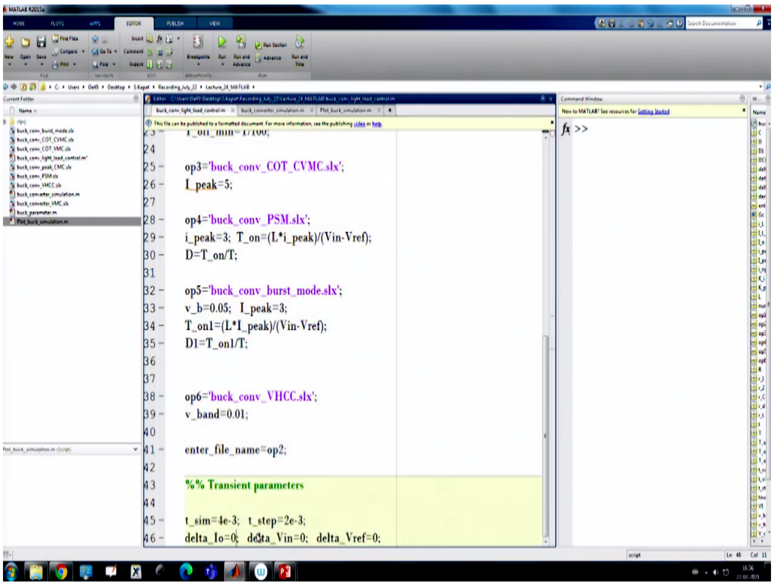

Now, I want to show under 100 milli ampere. Now, instead of load transient we apply a supply transient. That means, it is initially let us say it is initially for example, 8 volt or maybe 6 volt. Now, your input voltage has change to I applied another transient of 6 volt.

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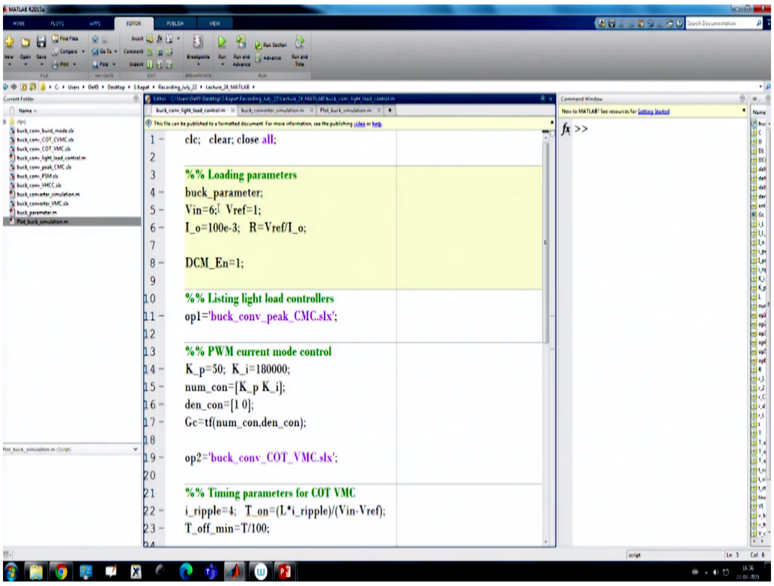

And let us run and see what happened. That means, I have increase the input voltage from 6 volt to 12 volt.

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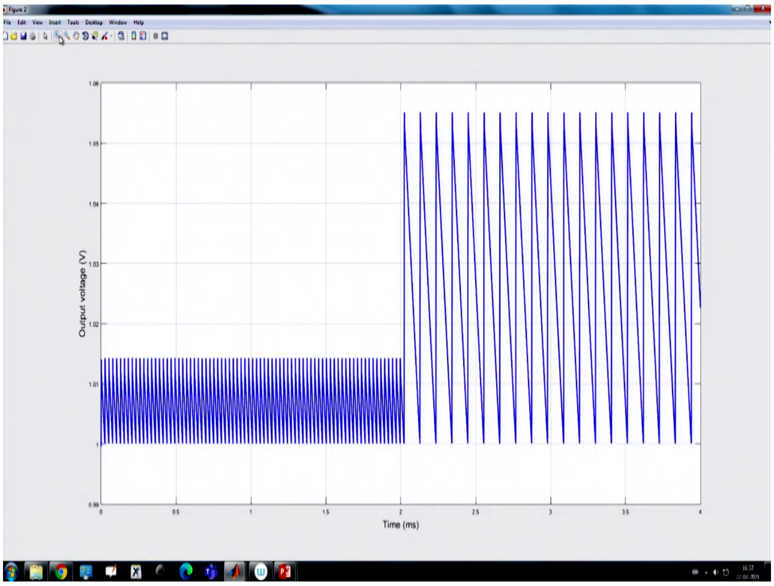

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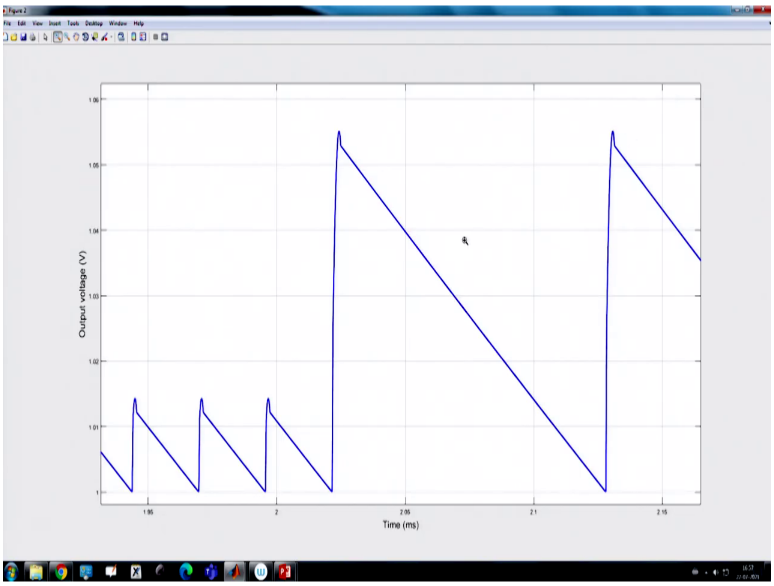

You see that due to the increase in the input voltage the ripple has increased significantly and it has a quadratic effect. And which actually goes beyond the ripple specification and it may violate the ripple specification ok.

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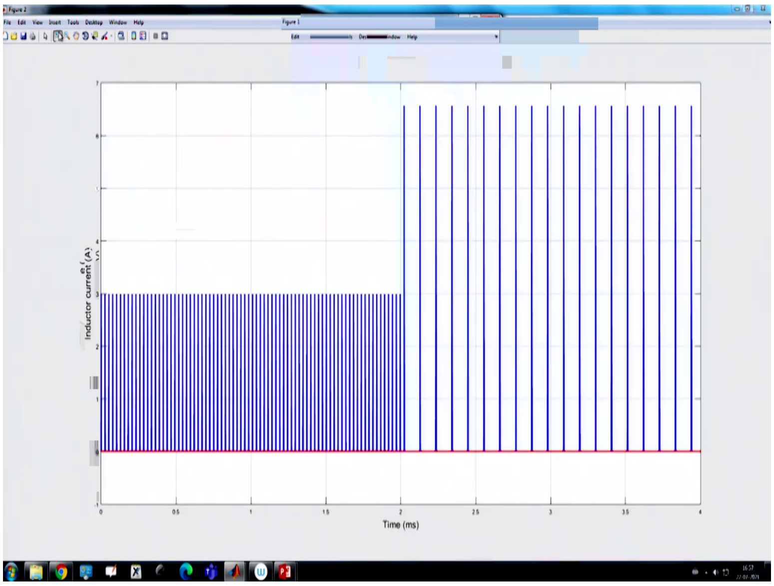

So, that is this is something which is not acceptable ok.

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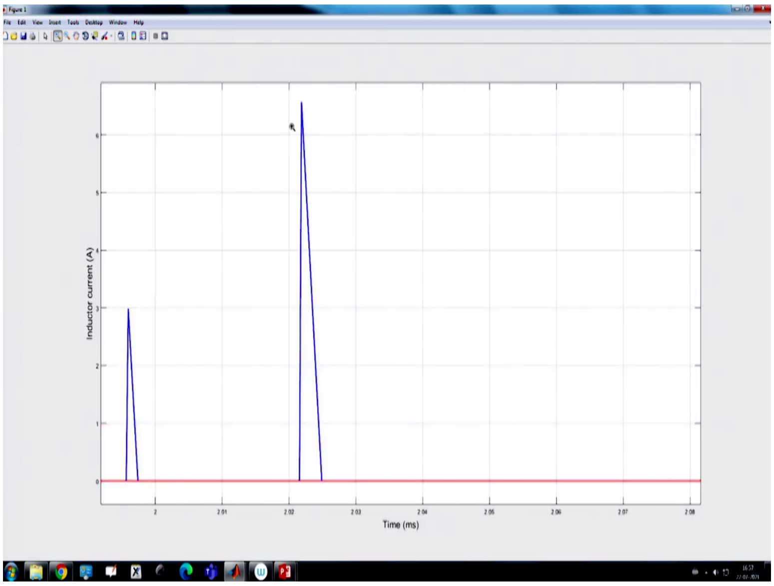

And also the peak current has increased drastically and it may go beyond the current rating of the device because if you design for low current application. Then, what is the solution? So, this is one of the drawback if you set the peak current directly using a on time timer. But, now if we can adopt the on-time then we can reduce the ripple voltage impact ok when there is a change in input voltage. How do you do that?

So, we want to do using a peak current base approach where earlier our on time was set by a timer, but now we are setting the on time by fixing a current peak reference peak current reference. And if we keep the peak current reference and this is my actual inductor current; this is my actual inductor current inductor current when it hit.

So, if my input voltage and output voltage are constant then; that means, under steady state what is my and we already know the output voltage expression of a buck converter under constant on time control we have discuss in the previous slide.

So, this is our expression that I am rewriting again. Now, what is my on time? Here my on time will be my peak current by m 1, and what is m 1 for a buck converter? So, m 1 for a buck converter is V in minus V 0 by L ok V in minus V 0 by L. Now, if you substitute m 1 here then you will get this expression and if you substitute this T on expression here and the rewrite this delta V 0.

So, we will get like this where, this K v is the voltage gain where K v is the voltage gain V 0 by V in. So, under high input voltage because if you take 12 volt to 1 volt right and then your K v is 1 by 12, which is around 0.083 it is very it is smaller than 1 then; that means, if I take K v to be very low then my output voltage expression there.

So, this can be this expression will be simplified to this because this is very very smaller than 1. So, this can be approximated to be 0 and is 1. So, you see this expression shows that; that means, delta V 0 is L i peak square by 2 CV 0. So, it is independent of input voltage it is independent of load current; that means, it takes the benefit of both. And if we go to the my simulation case study again now I have implemented this logic using a peak current base approach.

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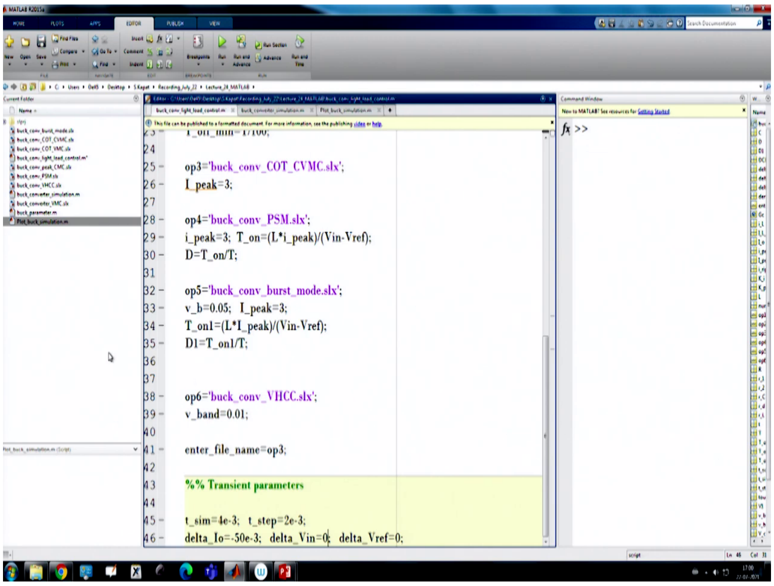

That means, let us use this technique this is a peak current base approach a constant on time. So, this is option 3 and I am using a 3 ampere to be my peak current and I am using option 3. And now, this option 3 first we will apply a e minus 3 a load transient.

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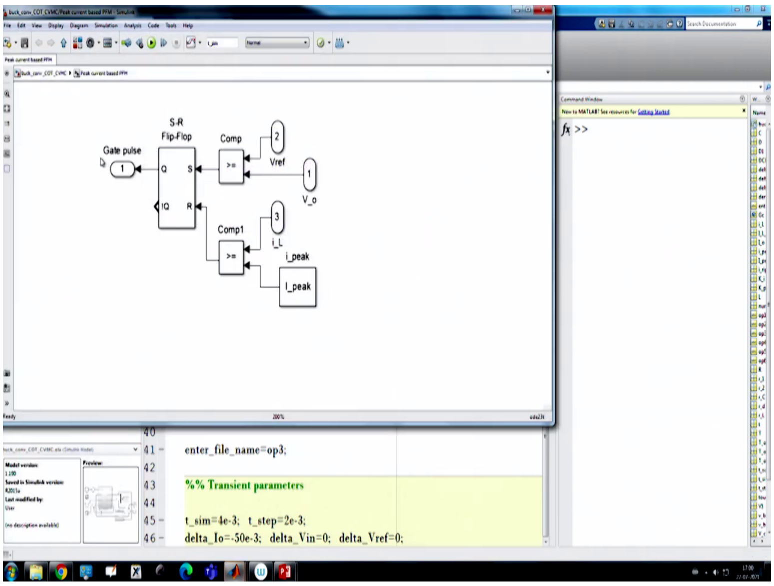

So, what is this?

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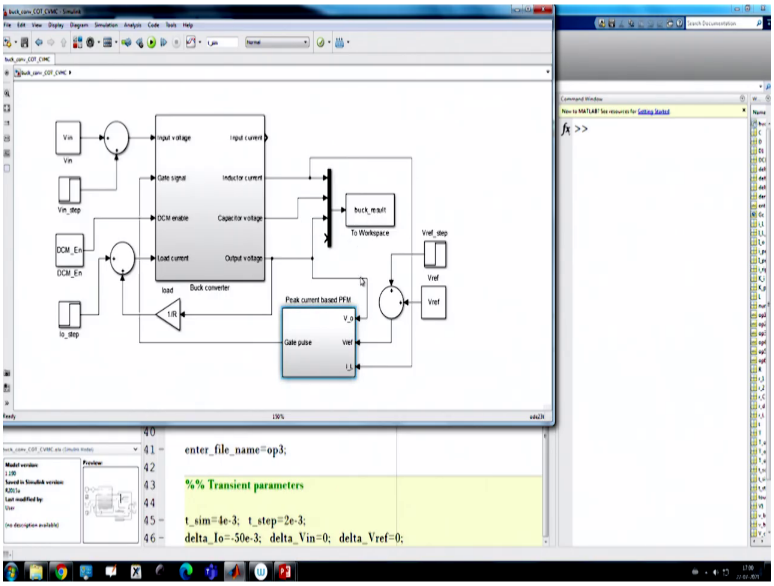

If you go inside I will show you here it is a constant on time, but on time is generated from a peak current reference this is my I peak and which you are setting from the MATLAB file here. So, if I run it.

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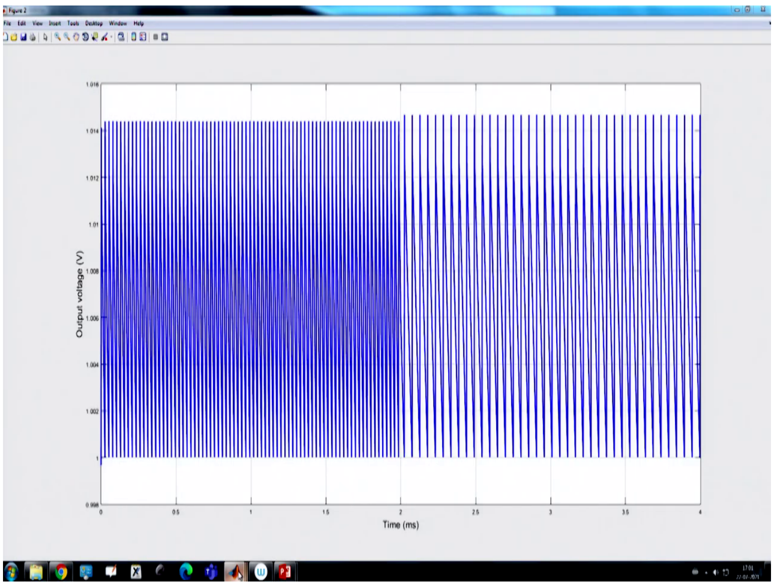

And if I run the load transient you see. Again we are setting the peak current to be 3 ampere and it is perfectly maintained; that means, your 3 ampere is maintained before and after load transient.

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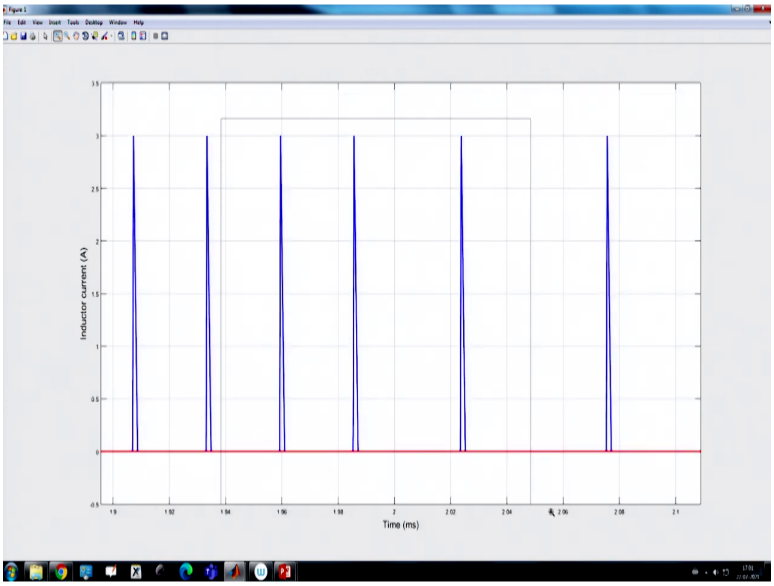

And you can see that your time period has doubled; that means, your switching frequency become half, which means it is consistent with our traditional constant on time where the frequency is linearly proportional to load current. When it decreases by 50 percent the switching frequency will also decrease by 50 percent.

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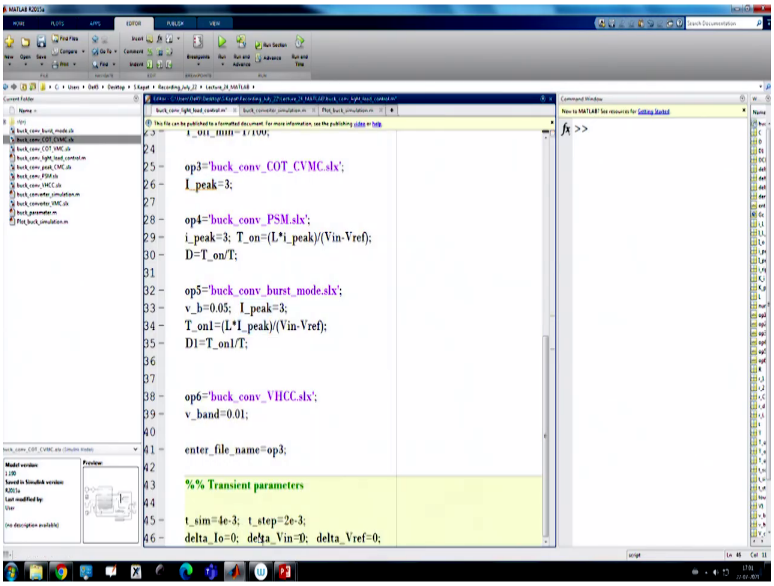

Now, we want to see what happen if you increase this input voltage; that means, you know now you are increasing the input voltage by some 6 volt to, initially it is 6 volt now to 12 volt. So, we want to run the same simulation which we did earlier.

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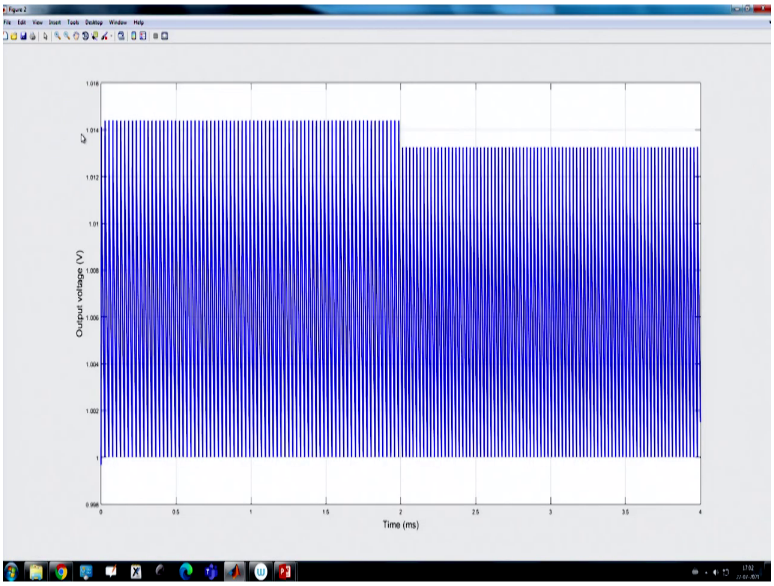

Now, you see there is a very minor change except.

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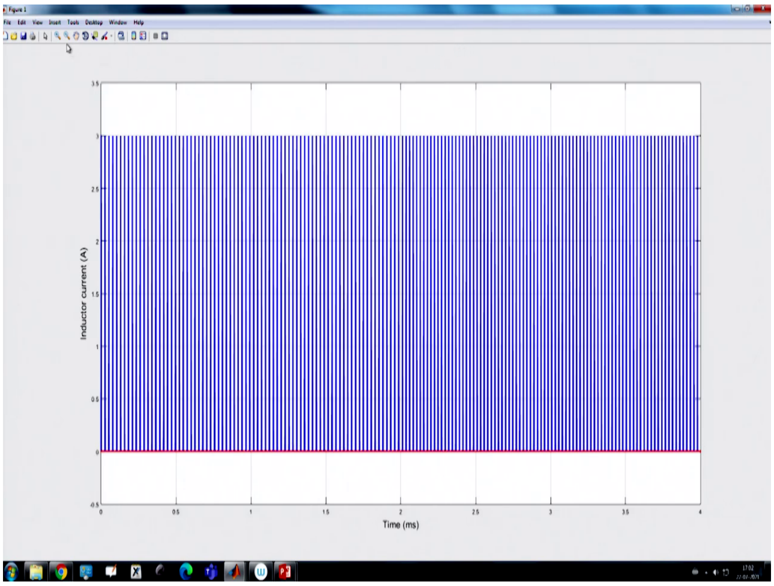

And if you check the inductor current wave form the current ripple remains same before and after transient and you see the current ripple remain same.

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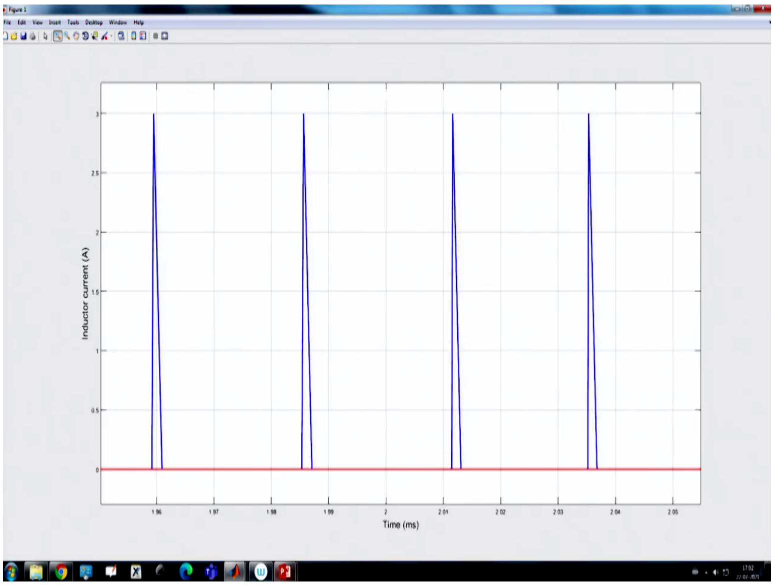

There is a change in slope, but the current ripple; that means, if you go to the output voltage ripple they are more or less same.

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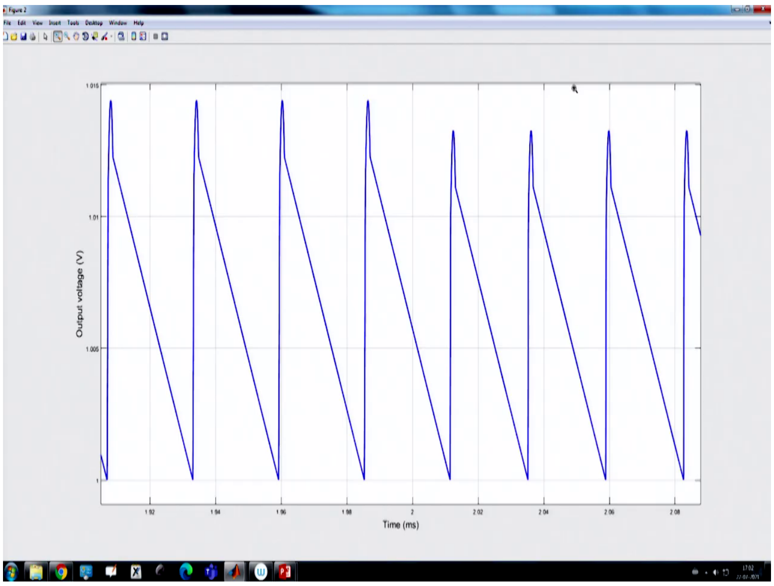

Earlier it was a drastically different waveform, but there is a slight deviation because we have used approximated expression not the exact, but here we can maintain the output voltage within the specified limit ok. So; that means, we can take the best benefit out of both constant on time as well as it can be adaptive on time when the input voltage varies.

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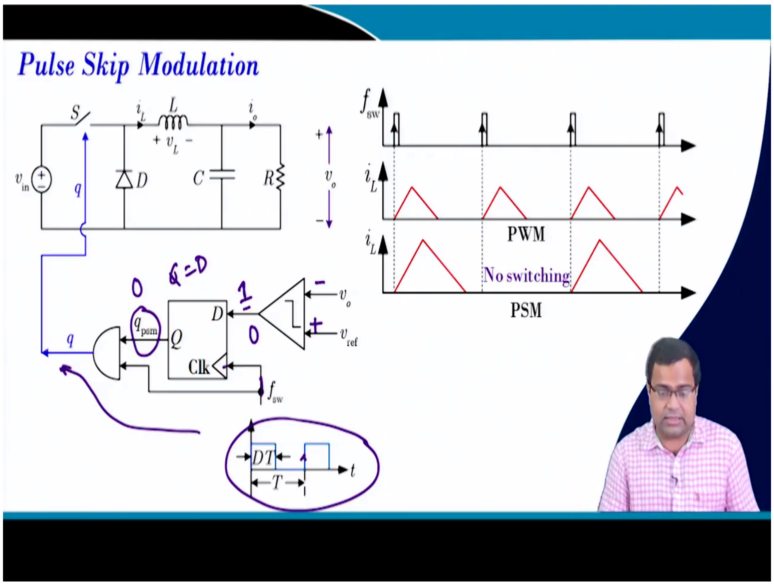

If you go to pulse skipping modulation it can improve the light load efficiency by skipping pulses; that means, we can go for charge pulse and skip pulse. So, this uses the same method of PWM this is a PWM, but with an additional logic of pulse skipping. So, if your output voltage goes above V ref; that means, if it is let us say greater than if this is greater than 1.

That means, if your reference voltage is higher than output voltage; that means, your output voltage is smaller, then this is high and if this is high at the rising edge of this gate D latch D flip flop the Q actually becomes equal to D it passes D and if it is 1 then q psm will be 1.

So, the q will simply take this clock; that means, the PWM clock, but suppose if the output voltage is higher than the reference voltage this will become 0, if this become 0 this q psm 0 will be set at the rising edge of this PWM clock and when it is 0 it will simply skip ok.

So, this is a pulse skipping operation and we want to see this pulse skipping operation using our MATLAB simulation.

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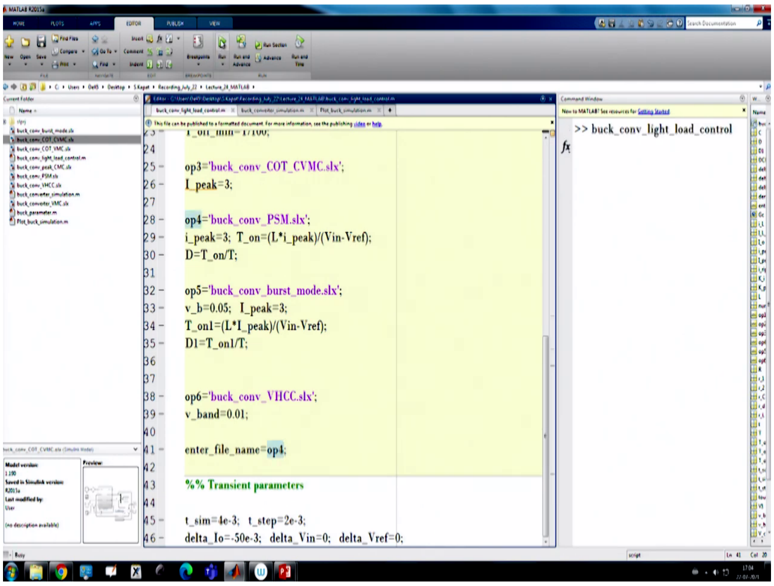

So, we can go back and here we have a pulse skipping operation here. So, again I am making a load transient of 100 to 50 milli ampere and we are going for pulse skipping. So, my pulse skipping is option 4. So, I will choose option 4 this is my option 4. Now, I will run it and check the simulation this is now under pulse skipping modulation.

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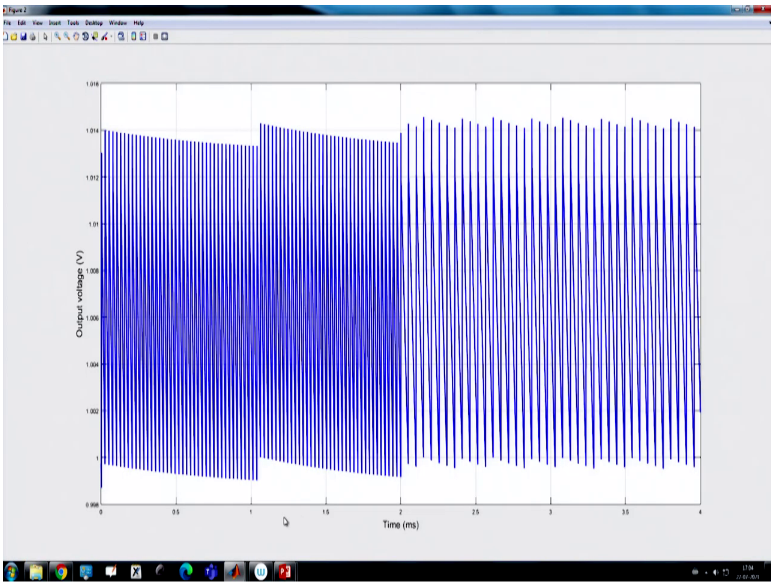

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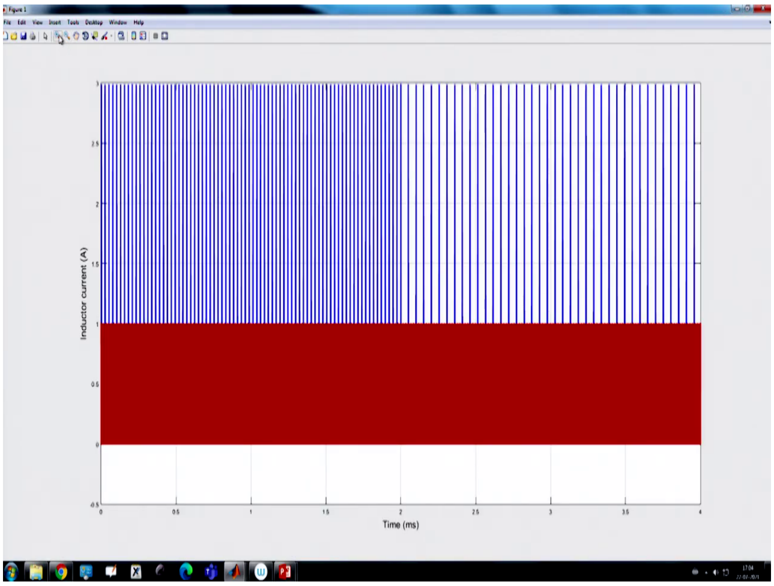

So, here I want to show you two things, first thing I want to first show you that.

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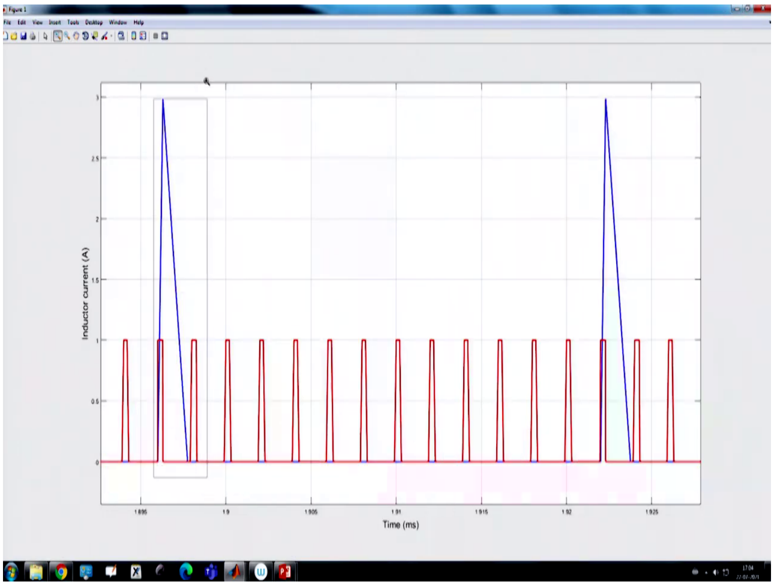

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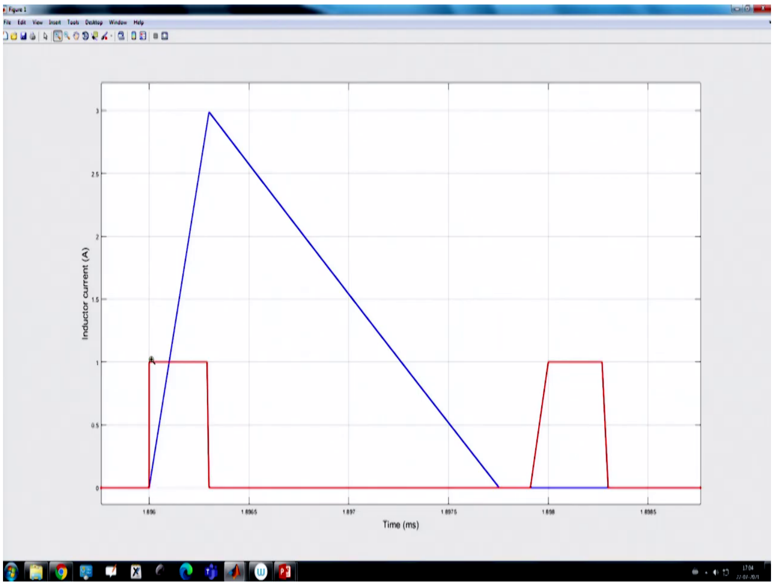

So, here this switch will be on during the on time of this PWM clock you see this is a on time of this clock the switch is on. And then next on time; that means, the red one is the actual PWM signal which is like a open loop duty ratio. And this is coming with a time period t which is same as our 2 microsecond time period after every 2 microseconds time period our clock is coming switching clock.

And we are using a duty ratio D for the switching clock which is set from this MATLAB logic ok. So, I am setting a duty ratio D which is coming because I want to ensure that for this duty ratio I want to achieve 3 ampere current I can directly set the value of the duty ratio, but here I am using an indirect logic. So, it is setting sort of 3 ampere current. Next after this you know whenever the next pulse comes.

So, here it will compare ok and let us say if we take you know some clock here let us say around 1 millisecond. So, let us consider in this clock ok. So, 1 millisecond ok or we may take close point where the actual switching happening ok. So, we will take here somewhere here. So, here we are talking about like a 4.94 switch is on, but then again the turning on of this pulse will come after a long time.

So; that means, first if you take between 2. So, here we call it as a charge pulse it will turn on for one cycle and it will go back to 0 and then inductor the current will that is pulse the switches the clock will be skipped; that means, switching clocking will be skip for this entire duration again it will be activated here. Because this logic is coming from you know this if I take this particular PSM logic.

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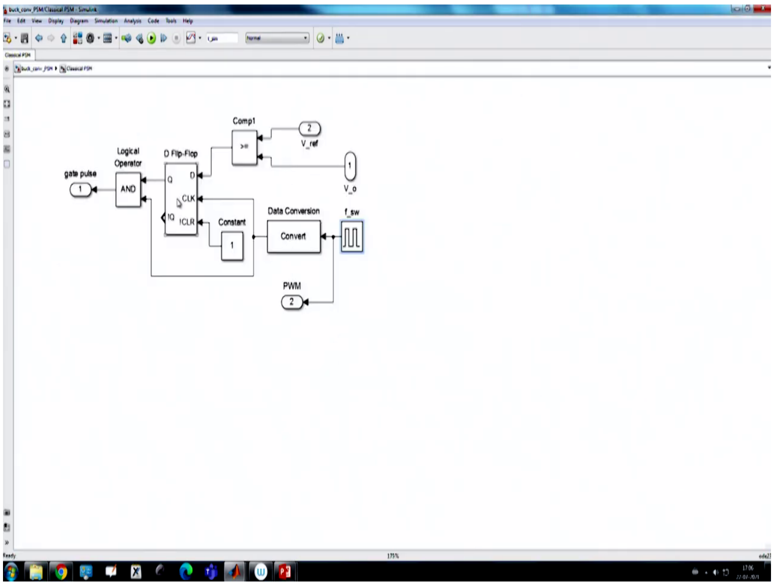

This logic is coming from this D flip flop; that means, this D flip flop and which you have discussed ok, and we are going to check ok.

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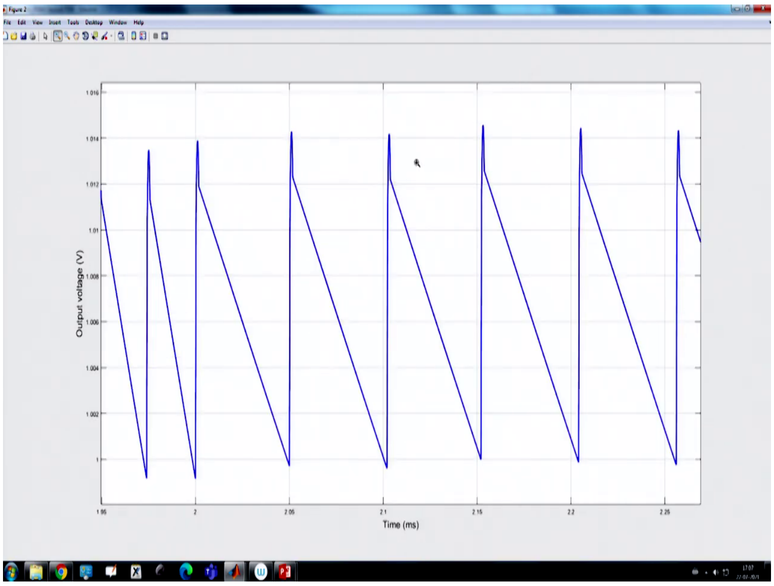

The another thing you will find here; that means, there is a charge and if the load current decreases more number of skip cycle happens. But this pulse skipping modulation has a problem of non monetary spectral composition you see, because a number of charge and skip pulse may not be exactly balance for any arbitrary load and input voltage condition. And if they are not exactly balance when after subsequent number of charge and skip pulse it can undergo an additional charge pulse or additional skip pulse.

So, that portion I am not discussing, but we have reported that this can lead to a non monotonic you know spectral composition and this can be addressed and we have you know develop of like a customized pulse skipping technique, which will you know overcome this technique. But the objective here the pulse skipping modulation can improve the light load efficiency by skipping more number of pulses and this aspect we have discussed.

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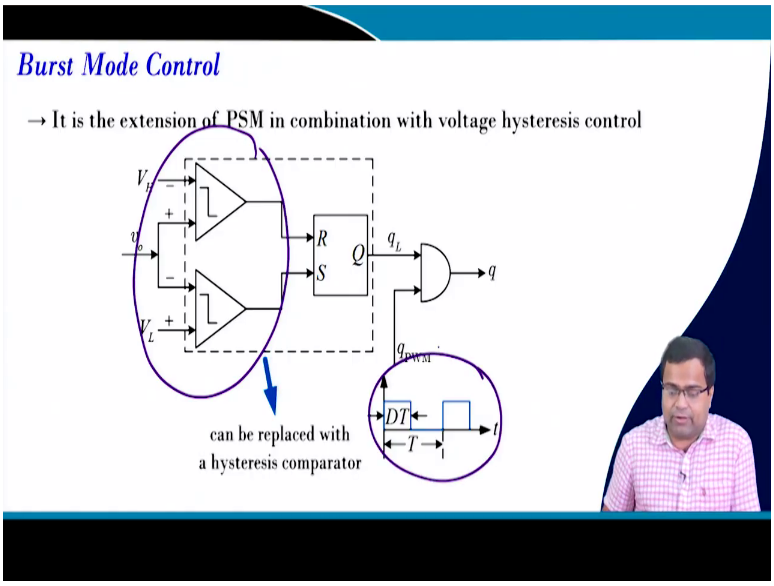

So, the Burst Mode Control in the burst mode control it takes the hysteresis control along with the PWM pulse that means.

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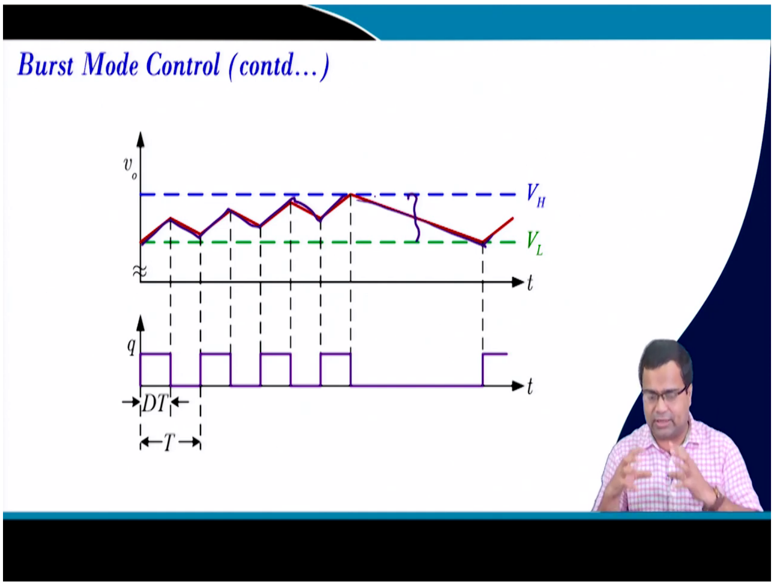

If I take the waveform if the output voltage is within this band ok; that means, if it is going down if it hit the peak limit it will go down when it hit the lower limit, then it gives multiple that PWM pulses until it hit the peak limit when it hit the peak limit again it will go down ok. So, this is called burst mode. So, it is a combination of hysteresis control as well as PWM control and we can go to our simulation of this. So, you also have a burst mode control which is option 5.

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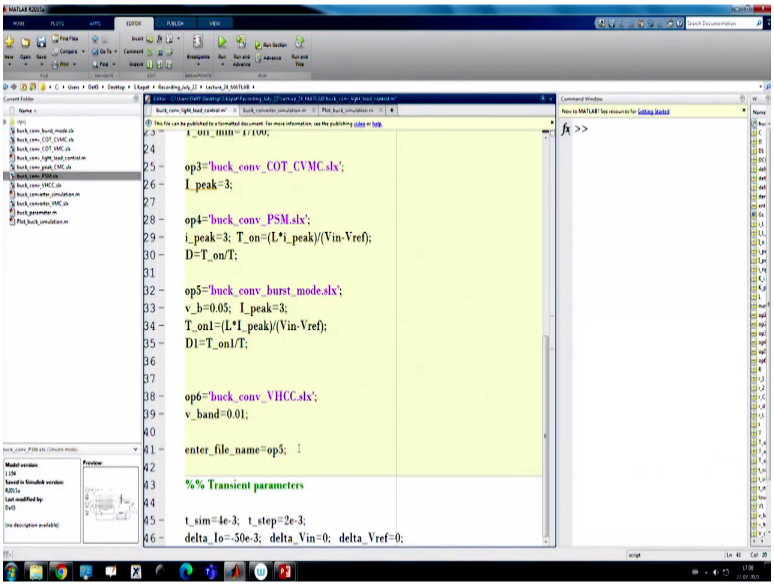

So, let us go to option 5 and check our burst mode control logic.

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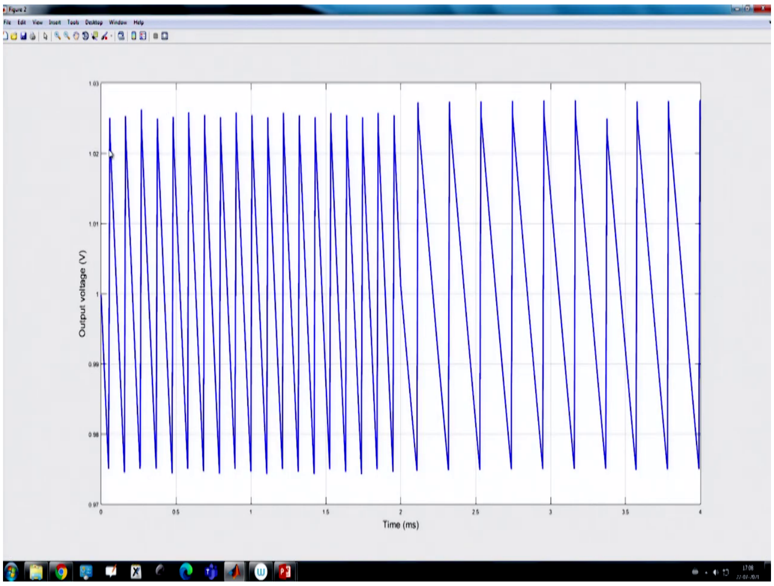

So, this burst mode control logic if you see that it has multiple charge pulse. So, you see within one cycle it undergoes.

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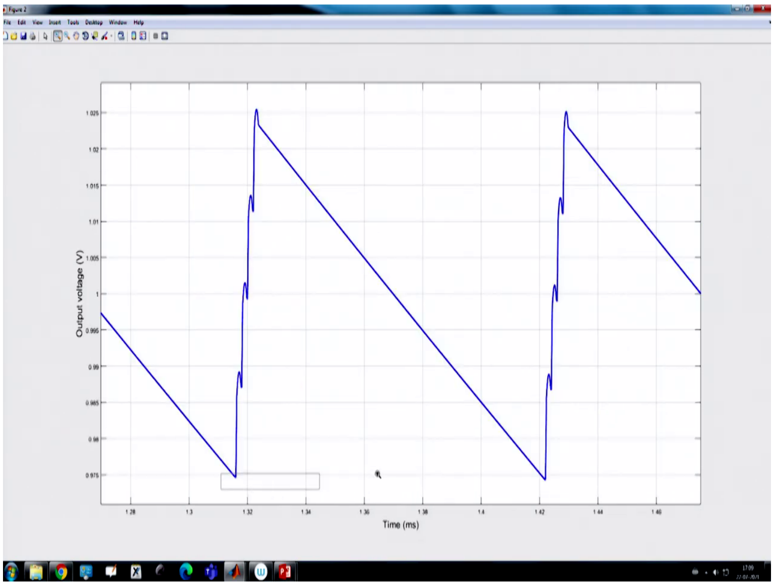

And there is a hysteresis band. So, when it hit the lower limit then it undergoes multiple PWM clock and then when it hit the upper limit it is simply turn off. And again this process continue ok and under light load you see the effective switching frequency is decreased or the time period has increase.

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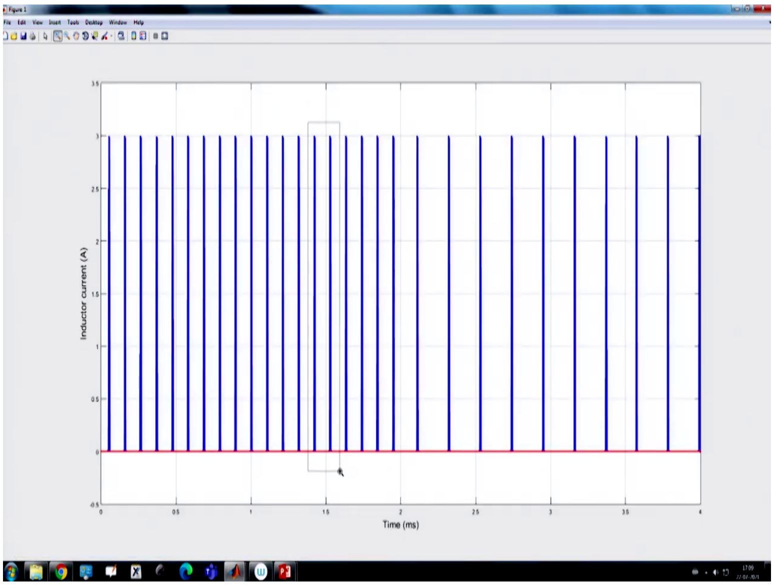

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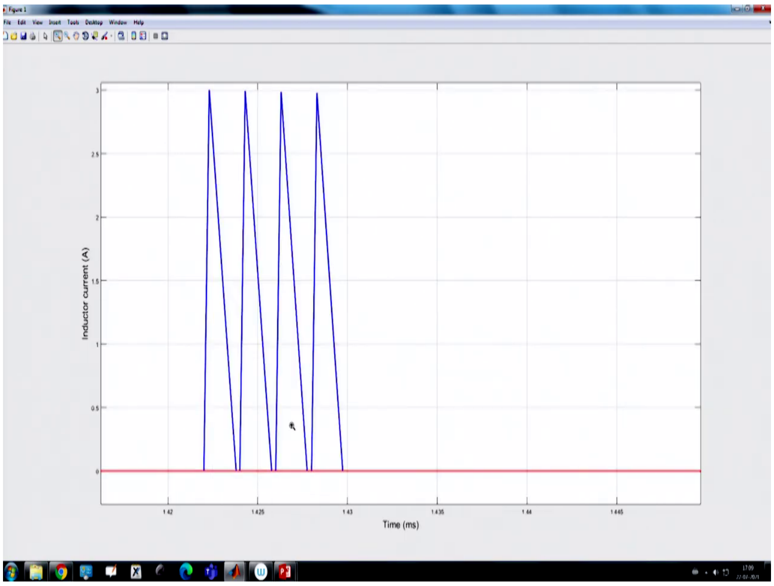

And if you go to the inductor current waveform I will show you if you zoom one particular part here, you will see multiple burst pulses will come when the output voltage will hit the lower limit. And this multiple burst pulses will rise will raise the input voltage and when the input voltage will hit the upper limit then it will simply again start falling and that time the cycle will be skipped ok.

So, here the skip cycle is happening by means of a hysteretic comparator. So, it is synonymous to pulse skipping the only difference in pulse skipping it was totally synchronized with the switching clock. But here it is an asynchronous operation between you know the charge pulse and the skip pulse is realized using a hysteresis block ok.

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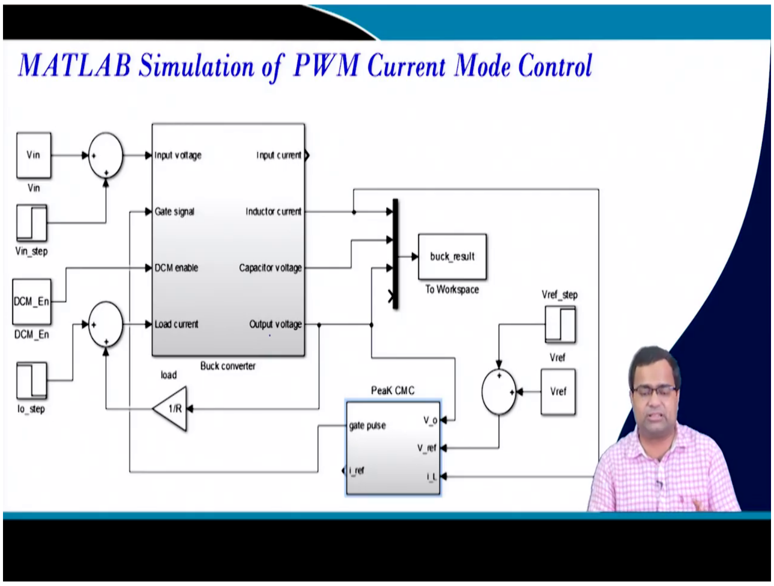

So; that means, we can go hysteresis and here I have shown the MATLAB simulation file.

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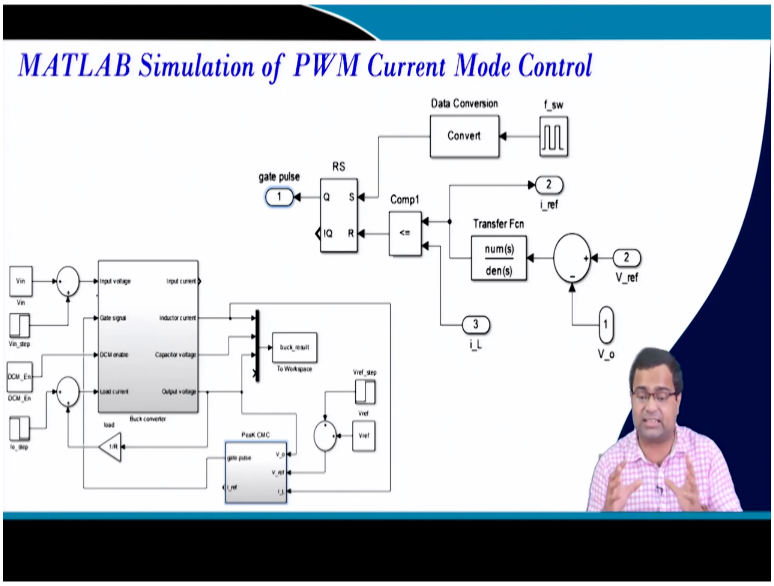

You can use the current mode control PWM technique under light load and this already we have discuss multiple time.

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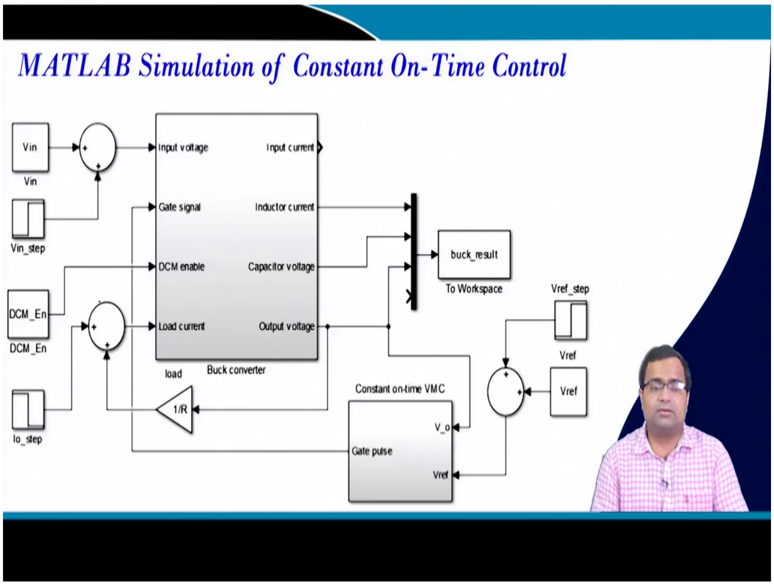

Then we can go for constant on-time control which already I have discuss. And if you go inside this block this is the block and in this case you remember since you are operating in discontinuous conduction mode.

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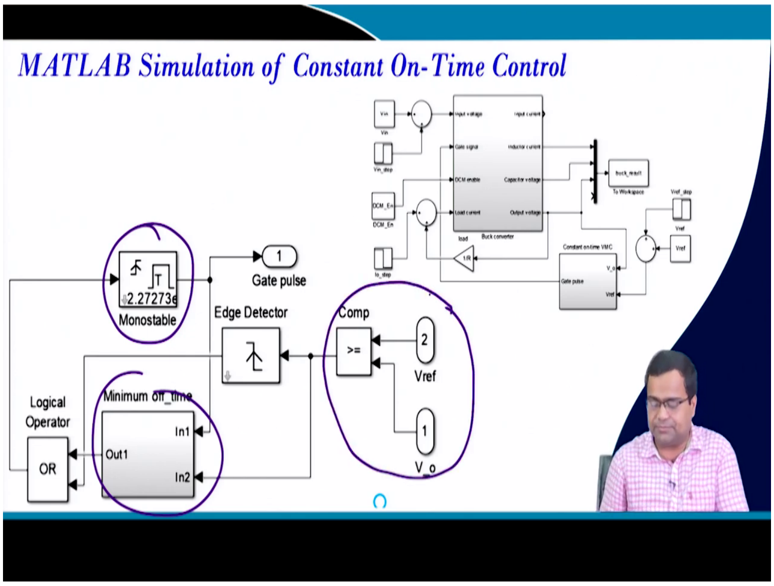

So, you have to enable the DCM; that means, if you go to of this. So, I have enabled the DCM at the very beginning; that means, I want to operate this buck converter like a conventional buck converter not asynchronous buck converter ok. So; that means, if you go to inside this block we have already discuss ok. And this is the control logic and this control logic again we have discuss that this minimum off time when constant on time is set here and this is a ripple base control the output voltage is directly compared to the reference.

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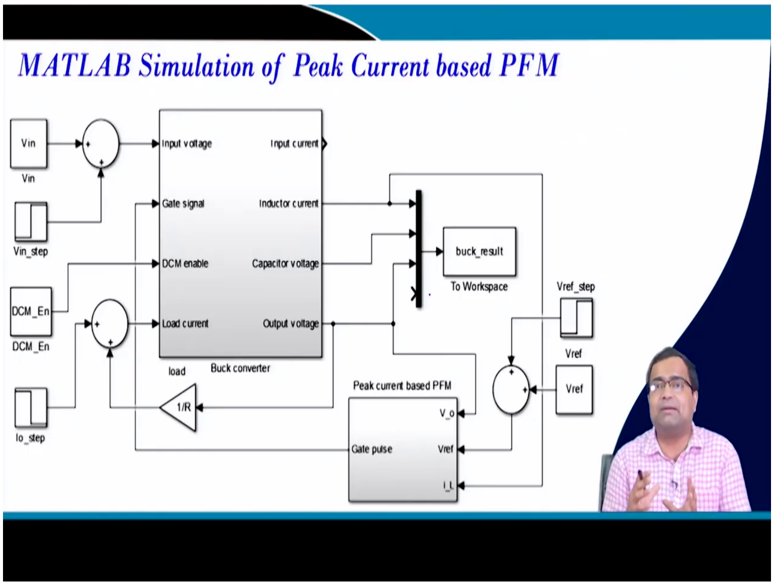

And if you go to the peak current base approach it is same as constant on time, but we are not setting the on time by a timer. Rather we are getting the on time by means of a current controller.

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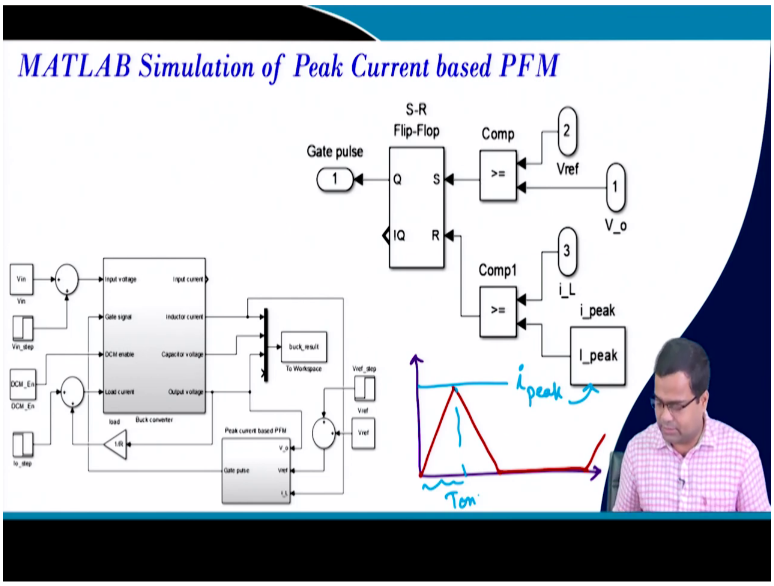

How? Here the on time is coming from by comparing the inductor current with a ok, by comparing the inductor current. So, there is an inductor current DCM like this and this is coming. So, this is i axis, so I can draw using ok. So, here it is my ok let me draw again. So, I am drawing here, and if I draw the inductor current like this and here I am realizing this peak current this is my i peak, which is this guy ok. So, it is coming; that means, here the on time is set by this constant peak current difference this is a constant current difference ok, as is a logic.

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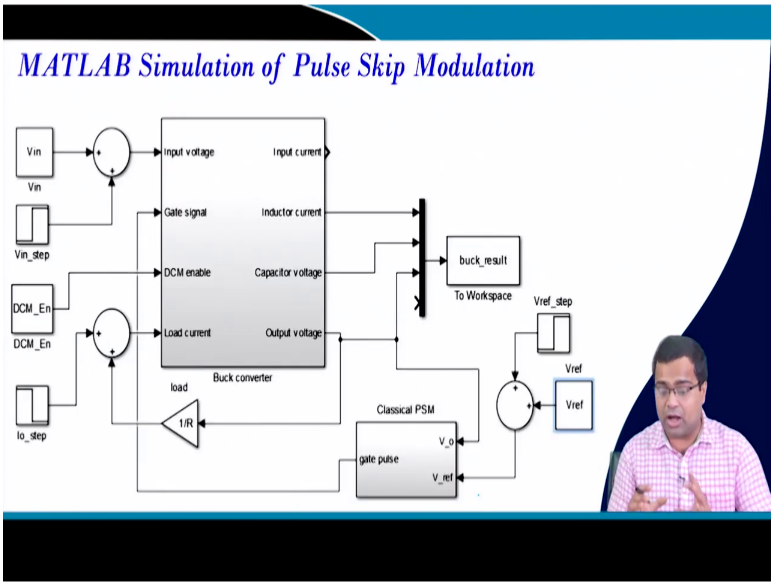

We can also do pulse skipping I told you how to realize pulse skipping. So, everything is same only this block we are changing multiple time.

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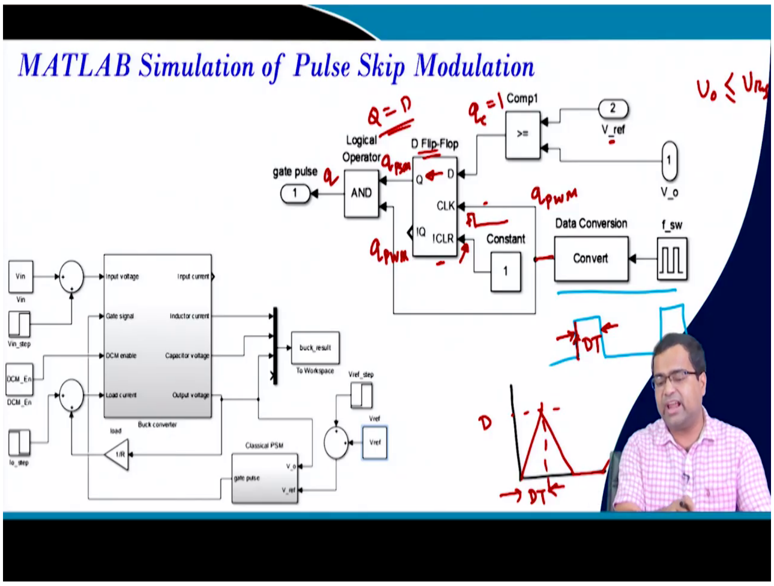

So, here pulse skipping this is the pulse which has a fixed duty ratio pulse; that means, so, this pulse we are setting some duty ratio D. So, we are setting some duty ratio D, D into T, ok. So, it is your choice how do you set D, but remember during this on time your inductor current will rise; that means, if I draw the you know the inductor current waveform during this time your inductor current will rise and then like this. So, if you set this is my DT time.

So, if you take a larger DT then it may have so happen that peak inductor current can be quite large. So, you have to be careful about this choice. Once this that mean this is my PWM clock; that means, this is my q PWM which is coming my PWM logic then this is my D flip flop.

So, D flip flop is activated this is my activated signal activating then I am comparing output voltage is a reference voltage. So, if my reference voltage is higher than the output voltage; that means, if my voltage output is less than equal to V ref then this goes high this comparator goes high.

And if this goes high at the edge of this at this edge of this clock because this is an this is a flip flop this work on the edges of the clock edges it will simply pass this; that means, your Q will become you know D it will store D in this case when the edge comes. And this we call it as a q PSM ok and then this is our q PWM and this is my effective q. So, if this PSM logic is 0 then its simply skip the pulse and if it is 1 it will simply pass the PWM pulse.

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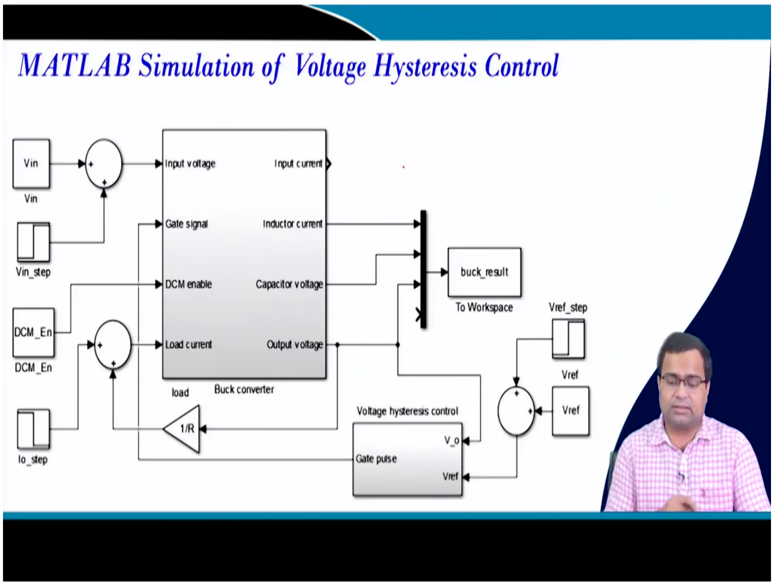

Then we can also implement voltage hysteresis control under light load where it is purely hysteresis band; that means, the voltage can be maintained within this is like your; that means, what we are trying to do we are trying to maintain the voltage ok.

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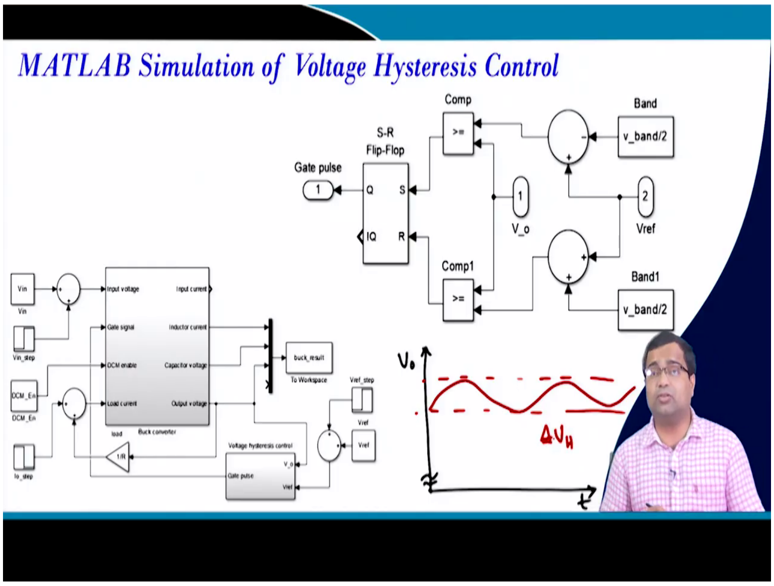

So, this is my output voltage this is the time. So, you are trying to maintain the output voltage within some hysteresis band sorry, within some hysteresis band. So, this is our delta V H band ok.

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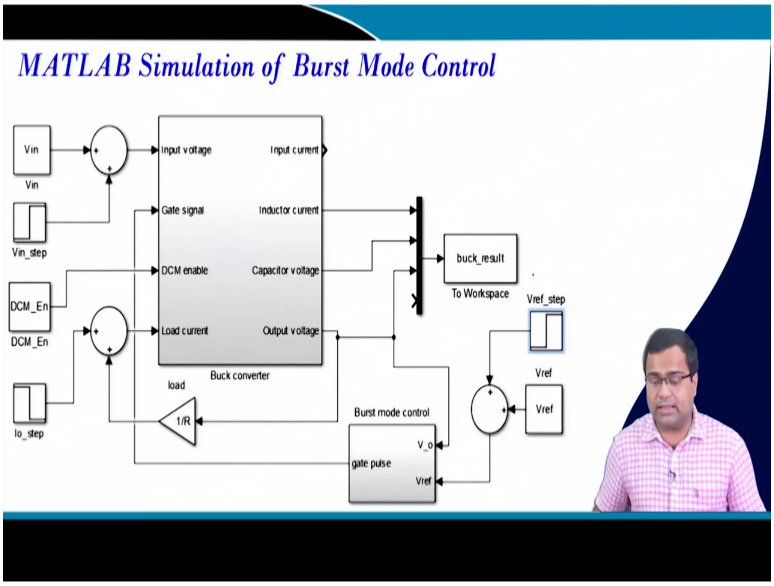

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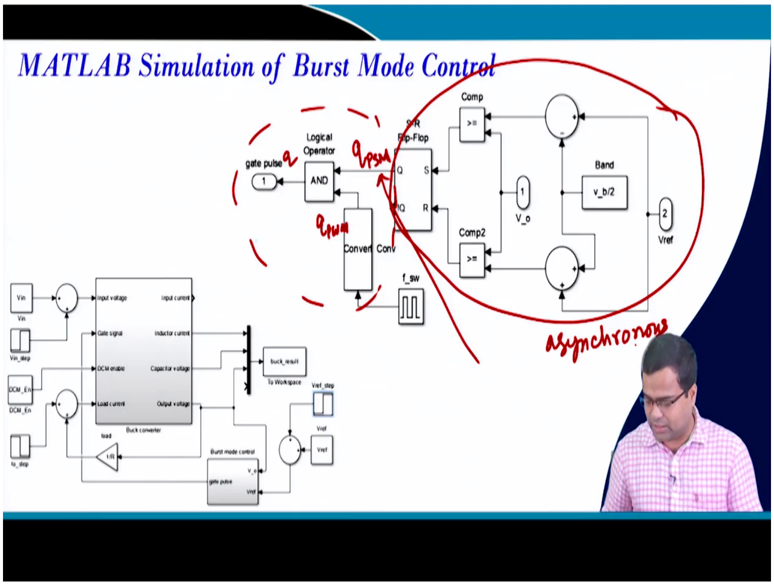

Then the burst mode we have discussed. So, the burst mode use the same logic of hysteretic controller ok and the hysteretic controller will act like a q PSM logic it is the same as earlier and this is like your q PWM logic and this is a q. That mean this is after this point it is identical to PSM, but in PSM the q PSM are generated in synchronism with the clock by putting a D latch and comparing V 0 and V ref at the every rising edge of the clock.

Whereas in burst mode this q PSM is generated by a hysteresis block so, this is an asynchronous block. So, this is an asynchronous block ok.

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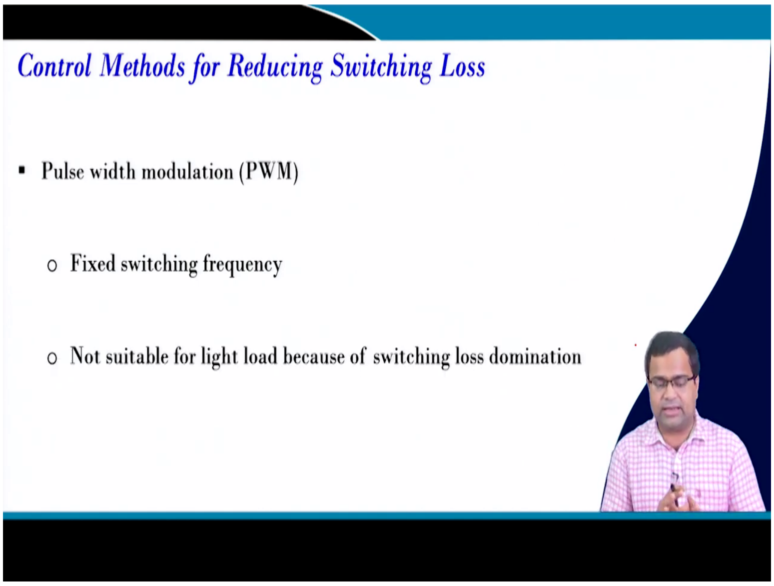

So; that means, the control method regarding switching loss reduction, PWM it is a fixed frequency it is not suitable for light load. So, switching loss domination then if you go to PFM variable frequency control this is good for light load, but not good for high load may not be constant on time offer switching frequency proportional to load current. High light load efficiency it is a very popular choice.

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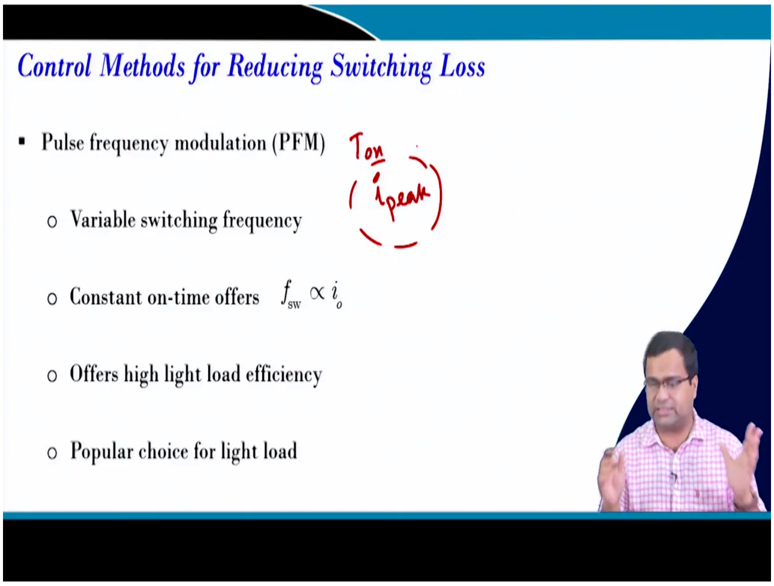

And we have two architecture one is purely on time set by timer another is the on-time set by peak current. And this is the most popular one because it takes care about the adaptation in the on time when the input voltage changes.

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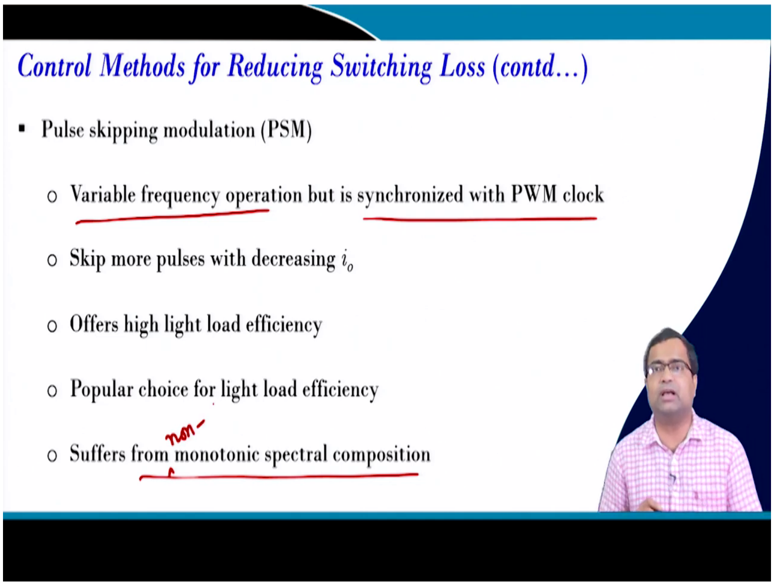

Then pulse skipping modulation it is a variable frequency operation, but it is in synchronism with the PWM clock that we have discuss skip pulses increases when the load current decreases it offer highlight load efficiency, it is also very popular choice. But only suffer from monotonics non monotonic suffer from non monotonic spectral composition.

Because, we saw some like you know little bit of you know the periodic behavior has not repeating because of extra charge and skip pulse after subsequent number of charges skip pulses, but that can be address there are method propose. So, then this technique is also very popular.

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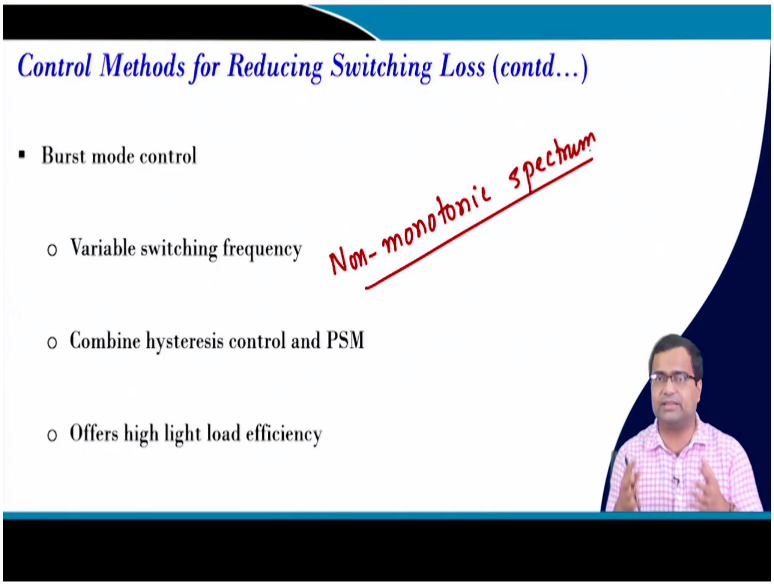

The burst mode control is also very popular it is a variable frequency control it combined hysteresis and PSM offer highlight load efficiency this technique is also very you know I would say non monotonic; that means, spectrum monotonic. That means in this technique it is very difficult to control the power spectrum that is why you know many industry may not prefer because the in managing the power spectrum.

Although on low power that spectrum amplitude itself is low, but here the problem is that you know that spectrum because there can be some non monotonic behavior that you have seen in the simulation.

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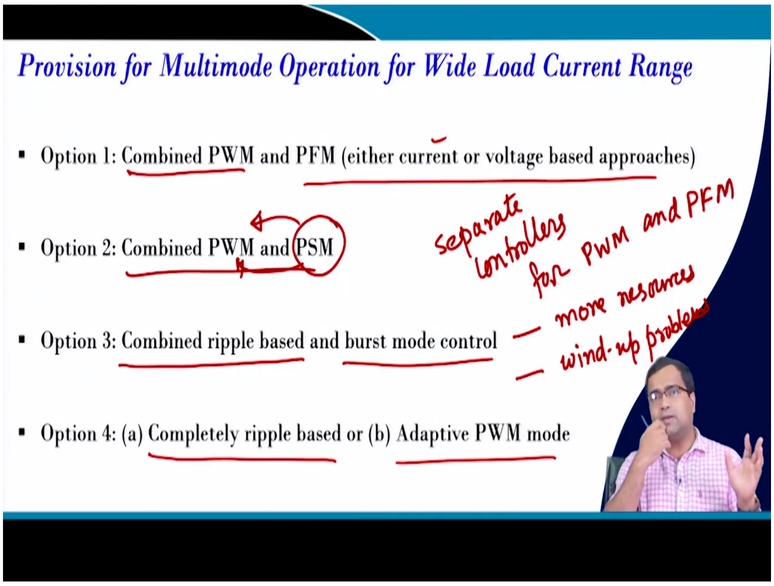

Now, provision for multimode; that means, 1: if we want to consider a wide load current range. So, the PWM will operate at high load PFM will operate at low load and here you can use a current based or voltage based approach. Combined PWM and PSM so, PSM technique is an integral part of PWM the only we have to enable the skip operation.

And if you make the duty ratio of this PSM coming from the loop then it is a you know voltage control or current control PSM technique and there are technique that that are proposed we have proposed multiple technique on that. So, you can combine this technique.

So, this technique can also be used for a wide load current range then combined ripple based and burst mode control. That means, if we use a purely ripple base let us say voltage hysteresis based control, then it will purely operate in voltage hysteresis mode when under nominal load current. And when go to light load in addition to ripple hysteresis control we can introduce some burst mode operation; that means, PWM clock.

And then option 4 either you can go for completely ripple based; that means, you go for constant PFM constant on time throughout ok or you can change between constant on time off time, but it is totally ripple based or you can go for adaptive PWM mode. That means you can adjust the time period of the pulse width modulator so that it behave like a constant on time control ok.

So, I want to show one of the work that we have propose here in our majority most of the problem in this multimode product they use separate controller for PWM and PFM as a result what are the drawback more resource are required, more resources are required. And there can be wind up problem when you change from one controller to other controller.

So, in order to avoid wind up controller; that means, if you want to achieve anti wind up or smooth transition or if you want to save resource the best way you use a single controller or at least the controller means the voltage controller for the whole operation for multimode and that is what we are going I mean this technique.

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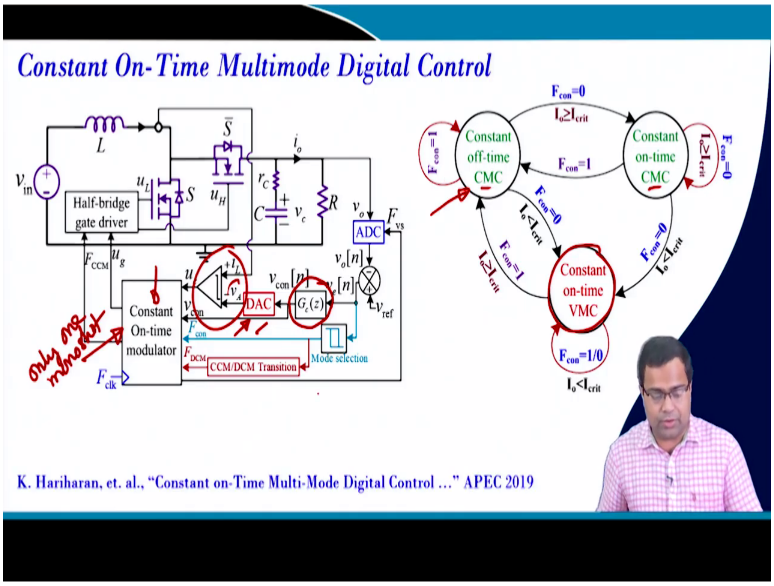

Here only it is a mixed signal current bit architecture where the voltage controller is digital and it is common and your current because it is in analog current loop. So, that DAC is there ok, and the current reference is coming from the DAC. So, the single DAC single controller the only and only one mono shot timer; only one mono shot timer and this timer can be loaded either with on time or off time.

If you want to configure to constant on time and constant off time, because this is just a digital number you have to just program it right rewrite the memory. Then the mode transition is just changing the edge of the clock because we have proposed a even base sampling and here if you dry a finite state machine.

So, when it go from light load to high load then I have discussed that the constant off time is superior than constant on time. In order to improve the step up transient when you go from high load to light load you can reconfigure to constant on time, remember in all cases our controller and you know the mono shot timer everything is common only the timer value can be updated ok.

And then when you go to discontinuous conduction mode because it is current mode control in DCM the current will be 0 at the base value. So, then voltage base logic will be enabled right and in this technique just whole modulator can be configured and you can adjust the on timing using an all digital PL.

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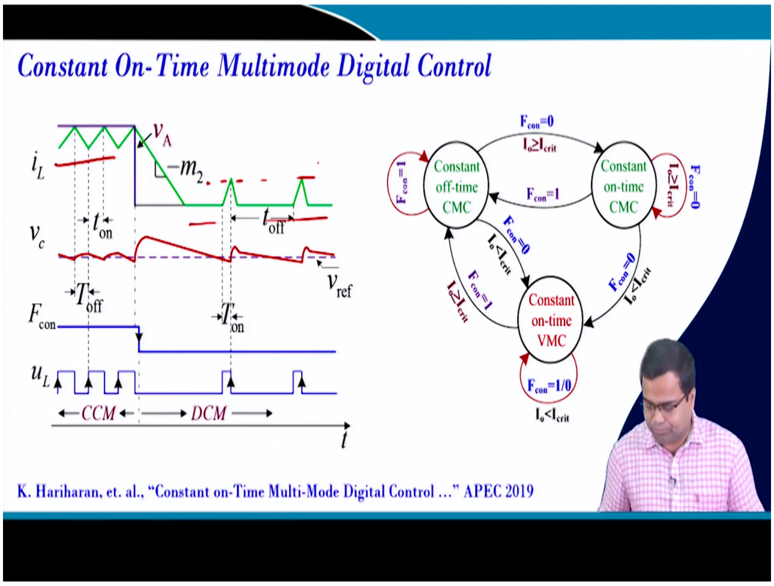

So, you can take; that means, under high load it will constant off time light load it is constant on time and you can use a peak current based approach, because you are generating the peak reference from the digital controller. So, you can use a current base PFM. So, that it takes care about the ripple efficiency everything that we have discussed ok.

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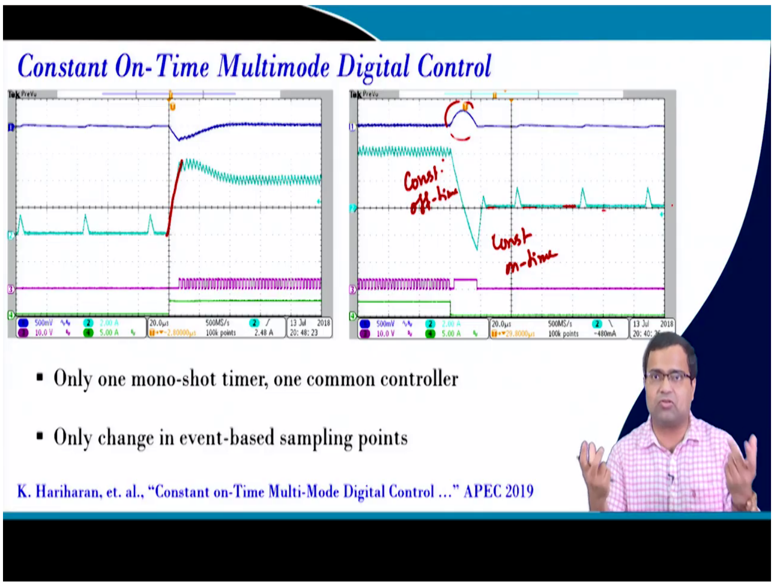

And the transient response; that means, when it go from light load to high load since we are enable constant off time. So, it is rising like you know almost without any problem and it is a boost converter and it offer because we may not be able to increase the gain significantly because of the right half plane 0 and it is changing drastically from light load to high load ok.

And when it go from high load to light load then we can actually enable, because if we go to this control light it is a boost converter that we are using. That means, you can we can use a synchronous configuration this is coming from constant off time to constant on time.

So, here it is constant off time and here it is constant on time and here we will allow the synchronous to operate for some time. So, that these charge can be extracted faster the overshoot can be substantially reduced and then it we bring back the dc operation when the switching frequency get automatically adjusted.

So; that means, it is only one mono shot timer, one controller and only the logic changes with the even based sampling we are using only the sampling point is getting changed. And this technique inherently achieve smooth controller transition because the controller is common ok.

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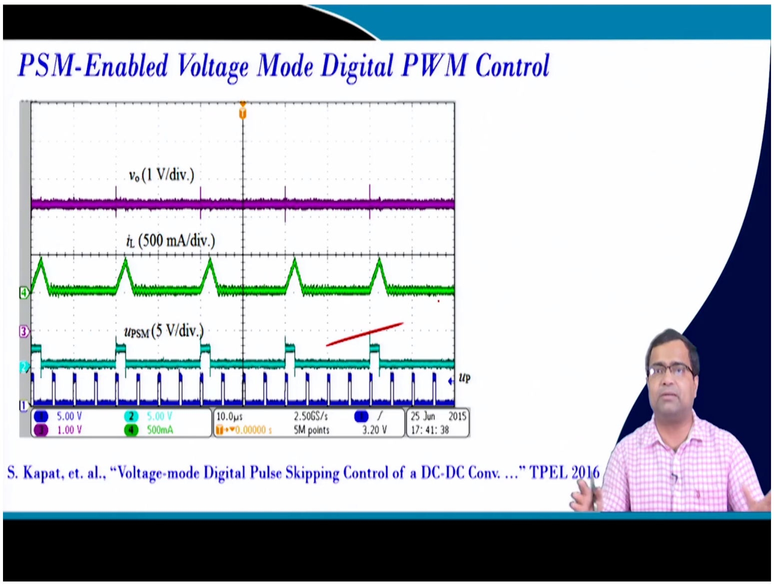

The other technique also we have proposed that in which that you can reconfigure; that means, a voltage control pulse skipping voltage mode where the number of charge and skip pulse, because we saw in pulse skipping there are the non monotonic spectral composition. That means the waveform was not repeating in every cycle there is a slight changes and it will create some kind of high periodic behavior.

But if we can configure the number of skip cycle and charge cycle in this technique you can apriori set it by which you can optimize the energy in efficiency and you can achieve perfectly periodic behavior.

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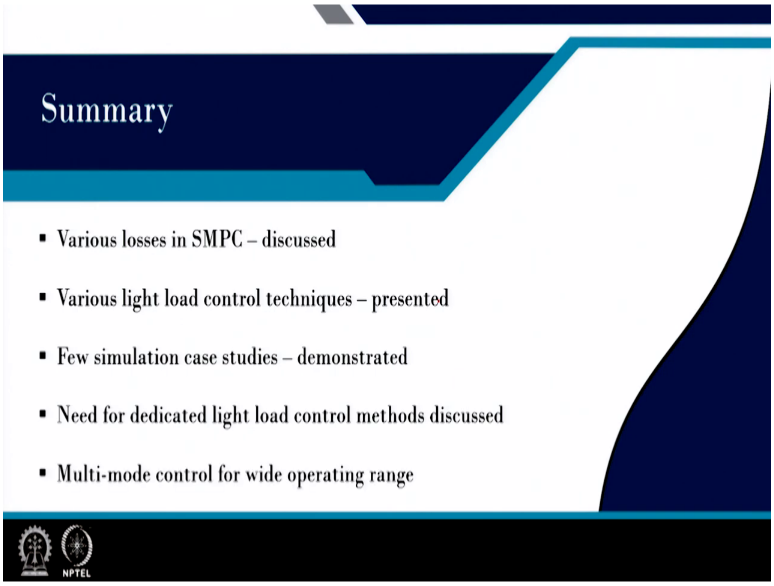

So, in summary we discussed various losses in switch mode power converter we have discuss various light load control techniques few simulation case studies also we have demonstrated then need for dedicated light load control methods are also discussed. And multi mode control for wide operating range we are discussed and we have also discussed few of our technique which one controller can actually be used throughout the entire light load and high load.

So, that it takes care about you know programmable switching frequency, high light load efficiency, first transient response and inherent current loop stability. So, it can be used for a wide load current and wide input voltage condition without need for any a ramp compensation. So, with this I want to finish it here.

Thank you very much.