Control and Tuning Methods in Switched Mode Power Converters
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Module - 02
Modulation Techniques in SMPCs
Lecture - 09
Variable Frequency Modulation Techniques

Yeah welcome back, so this is lecture number 9 and today we are going to talk about Variable Frequency Modulation Technique.

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So, in this lecture I am going to talk about Variable frequency control and which include constant on time modulation, constant off time modulation, Hysteresis control and some aspect of Steady state analysis.

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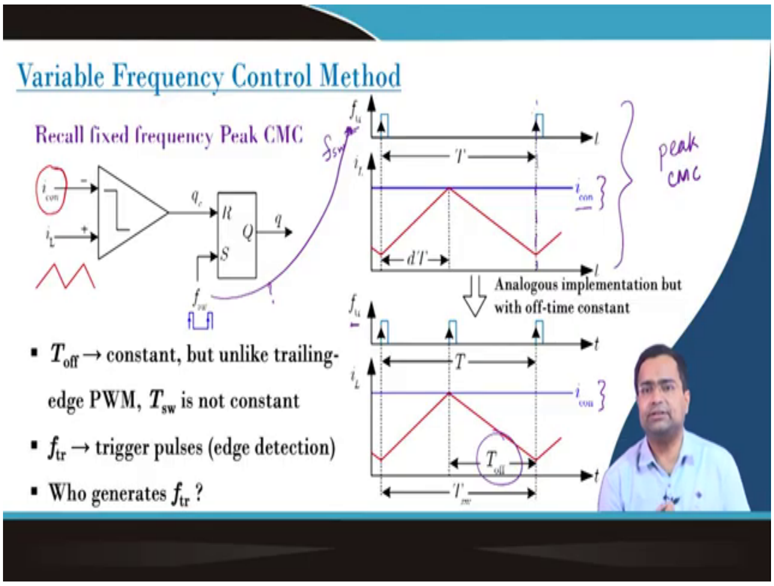

So, variable frequency control method I mean you know when you say variable frequency, because in the previous lecture we found that on time off time and total time. In pulse width modulation, we kept total time constant and we varied on time or off time like you know we saw in the previous lecture, like whether it is a trailing edge or leading edge modulation.

And in an analogous sense in variable frequency, also sometime we control on time by keeping off time constant, sometime we control off time by keeping on time constant, sometime we control both on and off time. So, this these are the like different techniques that we are going to discuss now.

So, if we recall fixed frequency peak current mode control where we have considered this is my control current, that means my peak current reference ok. So, this is my peak current reference. This is my peak current reference and this reference inductor current would be compared with this reference ok.

So, inductor current will be compared with this reference and the output of the comparator is used to reset. We have already discussed this in the fixed frequency control technique. Now, if we look at the waveform, the top waveform this corresponds to peak current mode control, and this is using fixed frequency trailing edge modulation. Where this in this fixed frequency modulation, this is our external fixed frequency clock that is a rising edge.

Whenever the rising edge comes, the switch turns on, like this pulse I am talking about, and the switch turns. Whenever inductor current reaches the peak current, here it is the control current, then the switch turns off and the switch remains turn off like.

And we also discuss the reset dominated set dominated like a weather reset dominant or set dominant that we have discussed. Now what I am trying to say in this case we have control peak current, here also we can control the peak current we can keep the same analogy; that means, we are controlling the peak current. But in this case we are keeping this off time constant ok.

So, in this case we are considering the off time to be constant. So, this is my off time that is shown here and on time is coming from where that is coming from the comparator when the inductor current reaches the peak current. So, T off is constant unlike in trailing edge modulation, where the time period was constant here time period will not remain constant.

Now how to generate the trigger pulse? So, earlier it was a switching pulse which was a fixed frequency clock, but here this trigger pulse is not a fixed frequency pulse how it is coming, who generates this trigger pulse?

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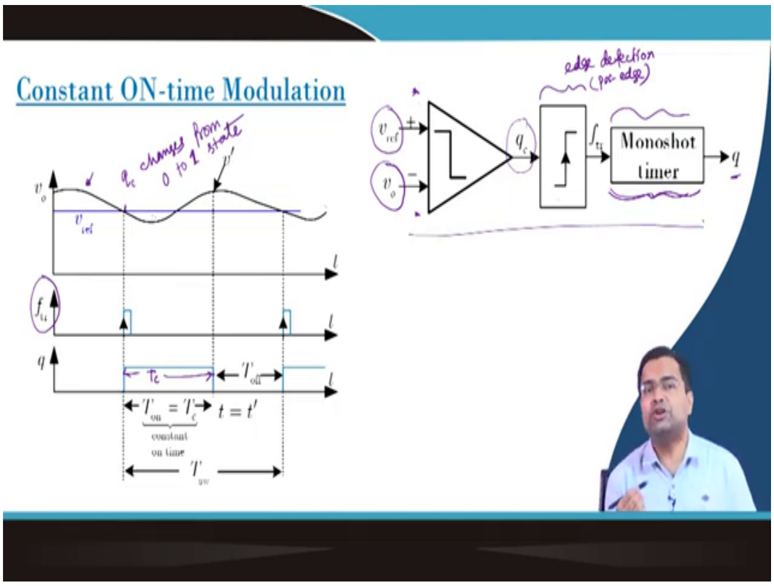

So, we want to first consider constant ON time modulation. What does it mean? If we take the output voltage of it can be a buck or a boost converter or any DC DC converter. If we compare this output voltage with the reference voltage and this is a comparator. And what does the polarity shows? This is a comparator and output of the comparator is a q c.

It shows the output of the comparator will go high when output voltage will be below reference voltage or reference voltage is above the output voltage. That means, when the positive terminal is higher than the negative terminal, then comparator output goes high and here we are detecting the positive edge of the comparator output that is the pos edge.

Then what we are doing? This positive edge is now it is going to trigger this monoshot timer. That means, monostable multi vibrator it is normally off whenever it accepts or when they receive a positive edge trigger signal a trigger signal, then it start counting because it has a preset on time value a timer.

So, it will remain active as long as the timer finishes counting; that means whenever it accepts a trigger pulse, it goes high at high state, which is an unstable state, at remain at high state until the timing value like counting is complete. When the counting is over, then it actually goes to the low state and then in that way we can generate the gate signal directly.

So, this is a waveform. You can see the output voltage when it is above the reference voltage. The comparator output was low. Whenever the output voltage goes below reference voltage, then comparator output q c will be high. When this point the q c will change state, it will change from changes from 0 to 1 state, it changes from 0 to 1 state.

And when it changes, then the positive edge is detected by this trigger pulse edge detection circuit. So, this is my edge detection circuit this detect my positive edge, not the negative edge. So, it is particularly pos-edge or the positive edge.

So, then it activate the monoshot timer and the monoshot timer remain active till this counting value which is the counter value which is set and during that time this output will be high and this is the one that means the on state of the DC DC converter. Then once the timing value is computation is over the timer actually finishes its counting, then the q goes low and it will remain low until this output voltage again reaches the v ref value.

That means as long as the on time you know the switch is on the output voltage rises and it goes above the reference voltage and whenever switch off, that means the voltage will start falling and then when it comes below reference voltage then actually again the trigger pulse detects a positive edge and it activate the monoshot timer.

Please remember the waveform here showing is the capacitor voltage; that means, even if you turn on the switch, it will not immediately charge that capacitor. Because we have discussed in the previous example like in a in previous lectures that inductor current if you take the inductor current a capacitor current waveform, the capacitor current actually start from a negative value as long as it goes it crosses 0 value that the voltage cannot rise.

So, when the capacitor current becomes positive, then voltage rise. So, that is why. So, this is basically the output capacitor voltage, now this looks like a very simple technique we are just talking about v 0 and v ref and just the edge detection circuit, comparator and monoshot timer and this technique is a very powerful technique. But in this form we may not be able to use it particularly during transient and that we are going to discuss.

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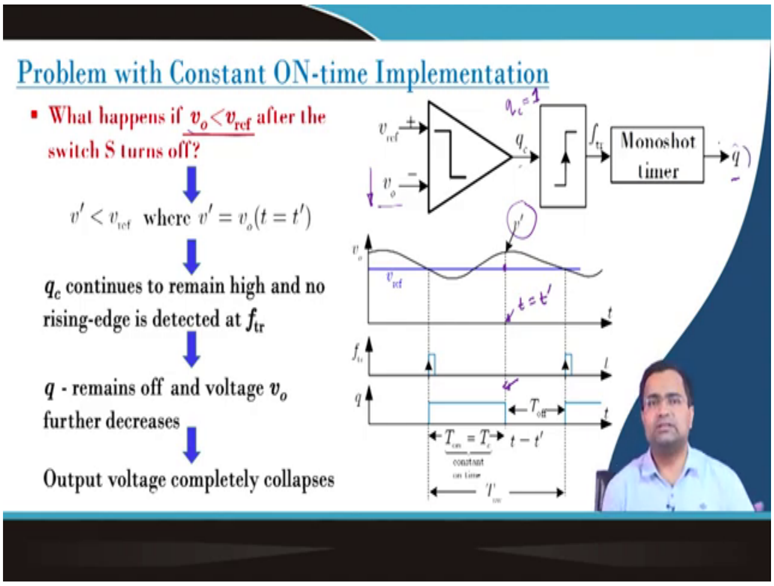

So, what is the problem with the constant on time modulation? Now we assume that when the switch turns off, that means I am talking about this phase when the voltage is v dash we are assuming the output voltage should be above the reference voltage and this is typically happened for steady state condition if you have sufficiently higher on time.

But now my question is what will happen if the output voltage after the on time is over; that means, your monoshot timer goes low if the v dash is lower than v ref. That means, what happens if the output voltage is smaller than the reference voltage after switch turns off? That means I am talking about this instant. What will happen?

So, the comparator output q c is low. In this case, it is low, there are no edges also monoshot timer also is not activated. So the timer remains continue, that means v dash is less than v ref at t equal to t dash. So, this is a time this is a time t equal to t dash and q c remains high. Sorry it should be low because v 0 is ok q c is remains high I am sorry it should be high.

Because here output voltage is lower than the reference voltage and if this is lower than the reference voltage, then output is high. But since there are no edges, it is to remain high. It remains. high there are no edges there is edge detection circuit could not identify an edge. So, the timer remains, the switch remains off.

So, there is no edge detected. So, q remains off this switch remains off and v 0 further decreases. So and what will happen the output voltage completely collapses because output voltage will continue to decrease and this will remain high and high and output switch remains off the whole system will collapse and this happened in the during the transient.

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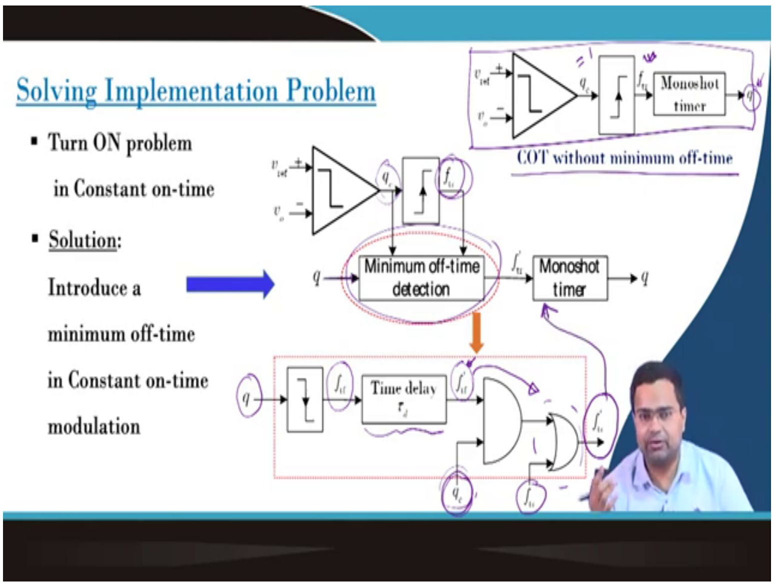

So, how to avoid such scenario how to solve? That means, in because in commercial constant on time controller you need to put. So, this is a straightforward that we discuss. It is in the very basic form now the turn on problem. That means we need to turn on the switch if we find that the output voltage is lower than the reference voltage, otherwise the voltage cannot rise. So, how to solve this problem?

The solution we need to introduce a minimum off time. That means, when the switch goes low, that means after the on time the monoshot timer completes it is counting value, the switch it will go off it will go off. And we need to identify at the falling edge of the q that whether the comparator output that mean this output is still high or not.

If it is still high, then we will wait for some time when the switch will be off. That is called minimum off time and then we again turn on when we need to create an edge trigger signal to turn on the monoshot timer.

That means to activate the monoshot timer, so by that way we need to introduce. How can I do that? So, now, earlier we use this trigger pulse directly as the input to the monoshot timer, but now it is not connected directly to the monoshot timer. So, it is there is an additional circuit, which is a minimum off time detection circuit. How does it work?

So, it accept it takes the input of the gate signal q and it takes the output of the comparator and it also takes the edge detection circuit output. That means, which is placed after the comparator output.

Then what it does? So, first is check whenever the monoshot; that means, when the switch turns off; that means when the monoshot timer completes its counting. That means, on time is elapsed, it detects the negative edge and that means it creates an edge which is a falling edge and that is delayed by a time delay tau d. So, you can use a delay circuit; that means you can use a shift register to delay by the delay amount that we want.

And, we created a pulse, after detecting the falling edge of the main switch and that we have delayed and that signal is ended with the output of this comparator. That means, if we find the comparator output still remains high because we have a problem, what was the problem?

Even after turning of the switch, if you find the comparator output remains high, no edge is detected, then we have a problem thus main switch was off.

So, first we check whether the comparator output remains high after the delayed the trigger pulse. That means, during this time we want the monoshot timer should remain off or the switch will remain off.

If this signal remains high then output of this AND gate actually passes this trigger pulse; that means, the delayed falling edge trigger pulse and that is ended with this trigger pulse. That means, the trigger pulse which was coming from here. So, ended means at that delayed interval it may not find any positive edge of the comparator output, but it will find a falling edge signal.

That means sorry this is a rising edge signal which was originally considered here this is a rising edge signal it is ended with this falling edge detection, which is detected and it is delayed by a minimum off time. And or operation of this falling edge delayed falling edge signal with the rising edge signal will be my trigger pulse for the monoshot timer for this monoshot timer.

So, these monoshot timer is now use now we can solve this problem. In fact, you know in subsequent lecture I will demonstrate this using MATLAB simulation.

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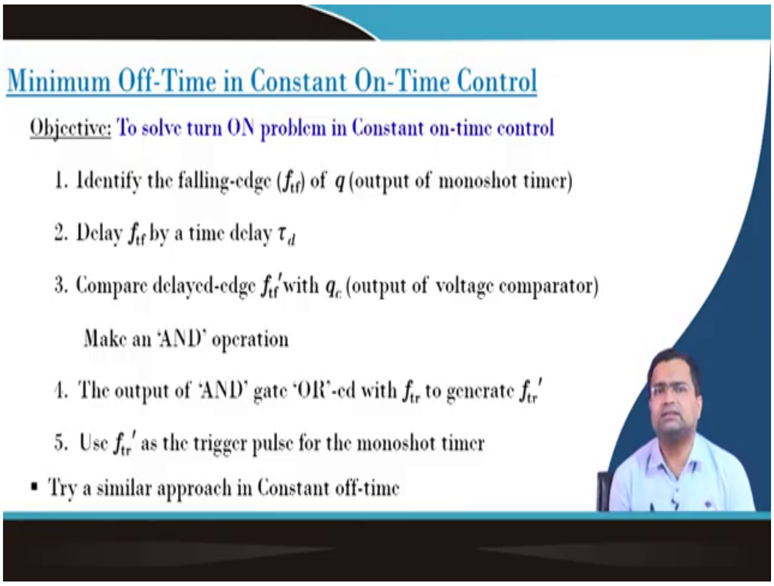

So that means, we can solve the problem of minimum off time in constant on time control problem. Now, minimum off time in constant on time control, how to summarize like what are the algorithm, the first we need to solve the turn on problem in constant on time control and this is particularly the case when after the switch is turned off.

If you find the output voltage is below the reference voltage, then we need to turn on again after a minimum of time and that has to be executed using an additional circuit.

And we have discussed this and we need to identify the falling edge of the q the output of the monoshot timer and we have to delay this signal by a tau d time delay. Then we have to compare this delayed falling edge trigger signal with the comparator output. If the comparator output still remains high, then we will make a AND operation.

And the output of the AND gate is applied to an input to an OR gate along with the rising edge trigger signal, which was originally there. And the output of this OR gate is applied to the input of the monoshot timer, so this acts like a trigger signal for the monoshot timer.

So, we can do the similar approach for constant off time. So, I will not discuss. In fact, this thing we will discuss in the MATLAB simulation, but for the time being I think we have we can address this on time problem in constant on time control.

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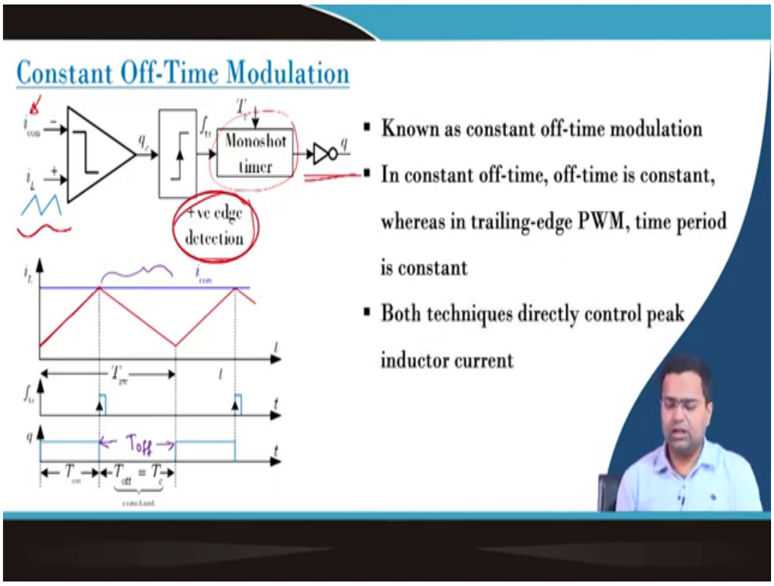

Constant-Off Time Modulation, if we take the current base constant off time modulation. So, this is similar to our peak current mode control.

That means you know this is the peak current reference and inductor current and it is compared using a comparator and output of the comparator, we are putting a positive edge detection circuit this circuit and then this edge is acting like an input to the monoshot timer. And here we are inverting that because we are using this as an off time not the on time, so you have to turn off the switch as long as this monoshot timer is high.

So, this is known as constant off time modulation and the waveforms are shown here when the inductor current reaches this peak current, then the switch is turned off and the switch turns off for the duration of fixed off time this is my fixed off time.

And after this off time is elapsed, then again, that means the switch is on; that means, this time the monoshot timer, this particular interval monoshot timer is activated, then switch again turns on and the process continues. So, we can have a similar problem; that means, constant off time; off time is constant. Whereas, that and it is compared to trailing edge PWM, the time period is constant in trailing edge here the time period is variable, but it uses a similar analogy of peak current mode control.

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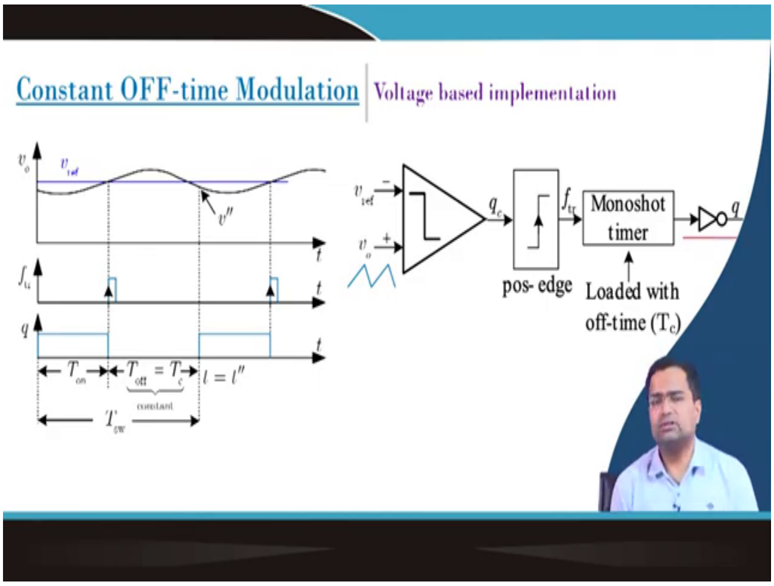

So, both techniques directly control the peak current. Now we can implement this constant off time using voltage based also, in this case we need to compare the output voltage with the reference voltage the same way and then the comparator output we are putting a like a positive edge detection circuit and then there is a monoshot timer and then again this is an inverted signal.

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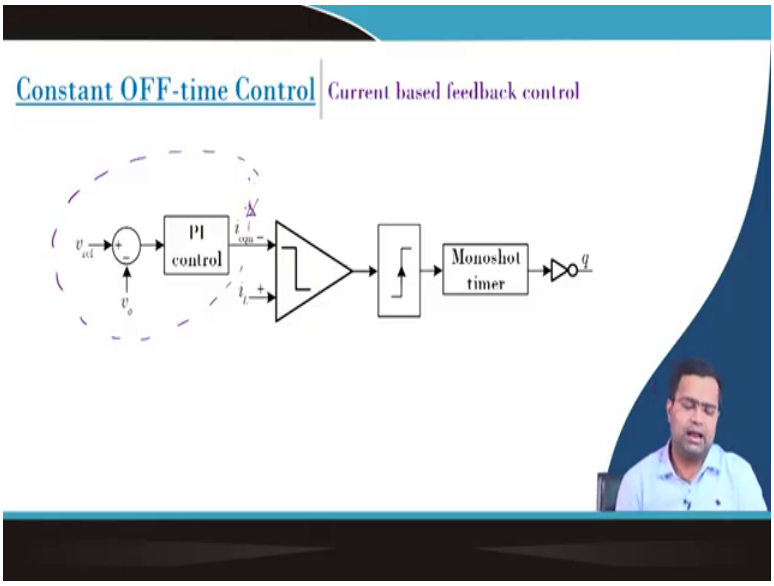

So, you can face a similar problem; that means, the current base constant off time control. Now, if we want to do closed loop control, then we can use a PI controller using the current loop that we will discuss in current mode control separately. But earlier we are using a fixed constant like a peak current, but now we can generate that peak current from the closed loop.

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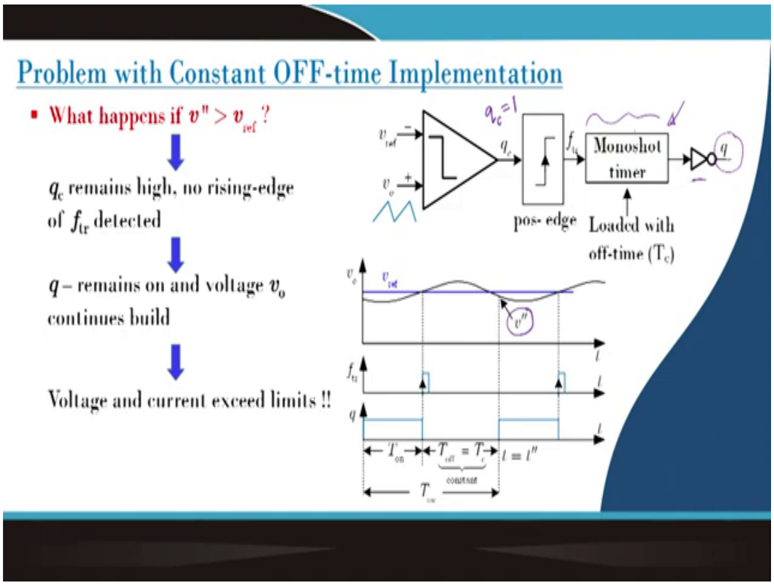

Again similar to constant on time, constant off time also have a problem of off time problem. That means, what is the logic here let us consider this v double dash and suppose we want that means when the switch is on we want that the output voltage should be lower than the reference voltage.

If output voltage is lower than the reference voltage, then this comparator output will be low when out and after the off time like you know monoshot timer completes its counting during that time the main switch is off.

After it completes counting, the main switch is turned on and when the main switch is turned on after sometime, the voltage should build up. But now when the output voltage goes above reference voltage then the comparator becomes high and it detects the positive edge and then again it activate the monoshot timer.

Now, what will happen if v dash double dash? That means after the switch turns off; that means your constant off time that timer is completes its timing. But after that, if we find if we find that the output voltage is above the reference voltage.

That means q c will remain high if q c remain high there is no edge detected here. If the no edge is detected, then monoshot timer cannot be turned on again. So, as a result, the output that means monoshot timer output is 0 and this q will remain high. So, if the q remains high, that means q remains high no rising edge is detected, then the output voltage will further increase.

And it will further increase and ultimately either voltage will exceed the limit, the specified limit or current will exceed its specified limit.

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So that means, we can you know the similar problem will arise in constant off time and how can you address? We can again consider a minimum on time for constant on time modulation off time modulation.

So, we can do the similar way in fact we can copy paste that block here and implement the logic we can plug in with this monoshot timer only difference is that here is an inverted logic.

So, we can do the same thing earlier case constant on time. It was a minimum off time that you have to introduce in constant off time you have to introduce a minimum on time ok.

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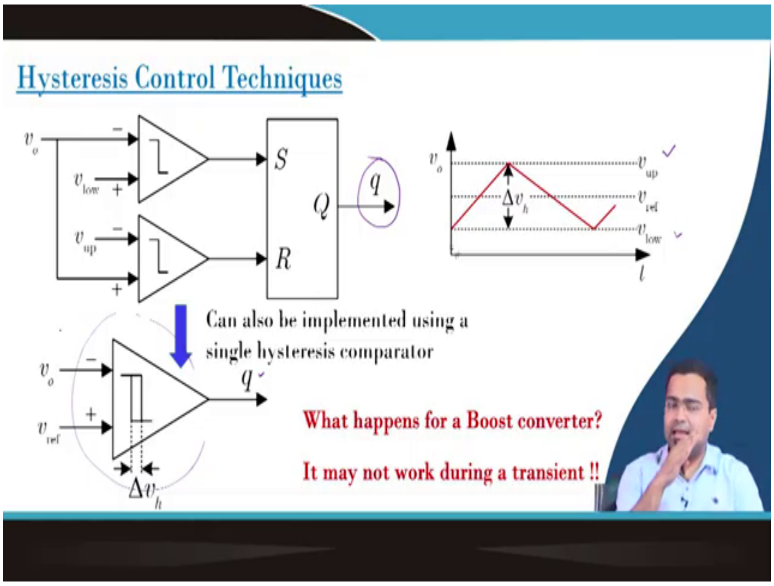

Now, Hysteresis control another thing so if you take a voltage hysteresis control, the output voltage is compared between its upper limit and the lower limit and accordingly the output gate signal can be generated. Perhaps this can be implemented using a hysteresis comparator. A single comparator is like a smith trigger and we can generate the gate signal for the converter.

So, we can do voltage hysteresis control. But this voltage hysteresis control, whenever we will take separately the hysteresis control, we will see for a boost converter this logic may not work particularly during transient, because it has a non-minimum phase 0.

So, you can find out that hysteresis comparator is one switching control logic and in this control logic since we are only taking the error of the output voltage at the switching function, it is independent of the current dynamics the switching function it can be shown that the 0 dynamics is unstable.

That means the 0 dynamics can be shown to be unstable. So, that is why this boost converter, the voltage hysteresis control should not be directly used unless we put a duty ratio limit or the switch limit. That means, in general, the switch will remain on an inductor will saturate during a step up transient.

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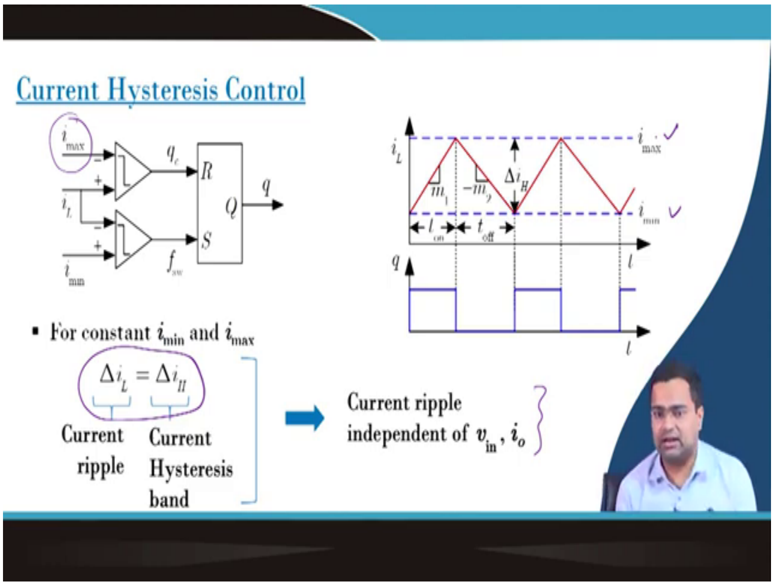

So, Current Hysteresis Control we can consider inductor current and again we can keep the inductor current between the upper and lower value the maximum and the minimum value. And we can now, if we use a fixed current reference like an upper and lower than the hysteresis band, the inductor current ripple can be made equal to current hysteresis band.

But typically that means, the current ripple here is independent of input voltage and load current. So, if we use a fixed current reference the inductor current ripple can be maintained within the reference and the ripple current will remain same for wide variation in the input voltage even if the load current varies. As a result the time period will vary because if the ripple current is kept constant, the time period will vary for different input voltage conditions.

But this condition cannot be met when we design closed loop control because the current reference one of the current reference will come from the outer loop the other current reference will be generated by subtracting by the hysteresis current level that we will discuss.

And the current reference will carry some ripple information of the output voltage and which will cause some ripple effect in the reference current. As a result, the current band will not remain constant, but of course the one band actually if you take the minimum one the lower value compared to the higher value it will be less than delta H. But the inductor current ripple will not be constant will not be the same as the hysteresis band that we will discuss.

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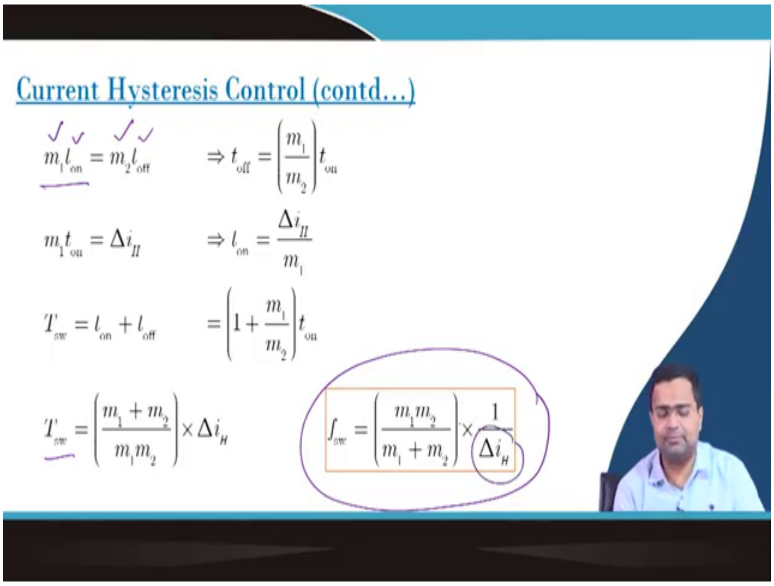

So, current hysteresis control we can derive all these equations from the inductor current ripple, the m 1 is the rising slope of the inductor current, it is the on time, this is a falling slope and the off time. And we can derive the total time and the total the frequency of the under current hysteresis control can be derived using this formula where this is the hysteresis band.

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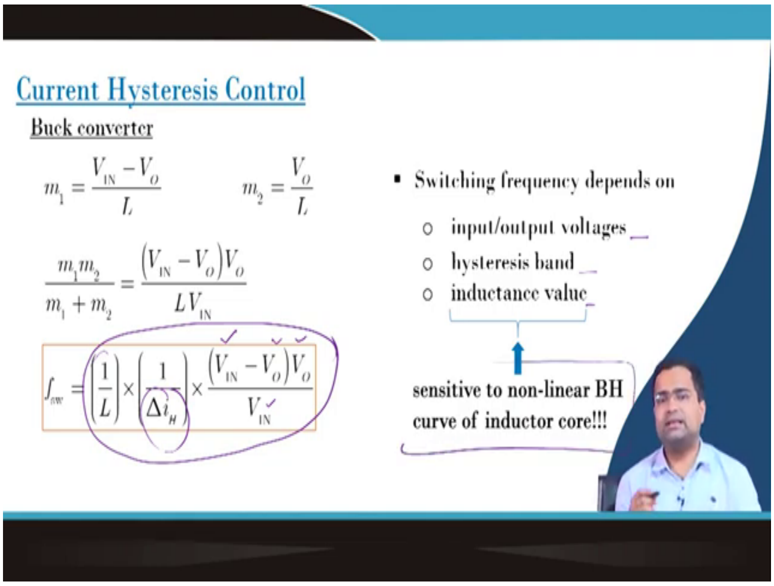

And for a buck converter, if we replace the rising slope and falling slope, then the switching frequency can be shown to be a function of the current hysteresis band, input voltage, output voltage as well as the inductance value.

So, switching frequency will depend on input output voltages, hysteresis band and inductance value. So, if we operate in a wide load current range, where the current through the inductor can vary widely and there can be some variation in the inductance value.

Because if you go to BH curve of the magnetic code of the inductor, it will not remain always in exactly the same slope, linear slope there can be slight variation in the slope. As a result the inductance can vary. And if we even try to operate at a higher current, there can be saturation in that there can be a core saturation effect.

So, which can drastically change the inductance value, under such condition this that you know switching frequency can you know very much become sensitive to the non-linear BH curve. That means, so you have to take care about the switching frequency if you want to regulate by using a separate control loop like a PLL phase-locked loop.

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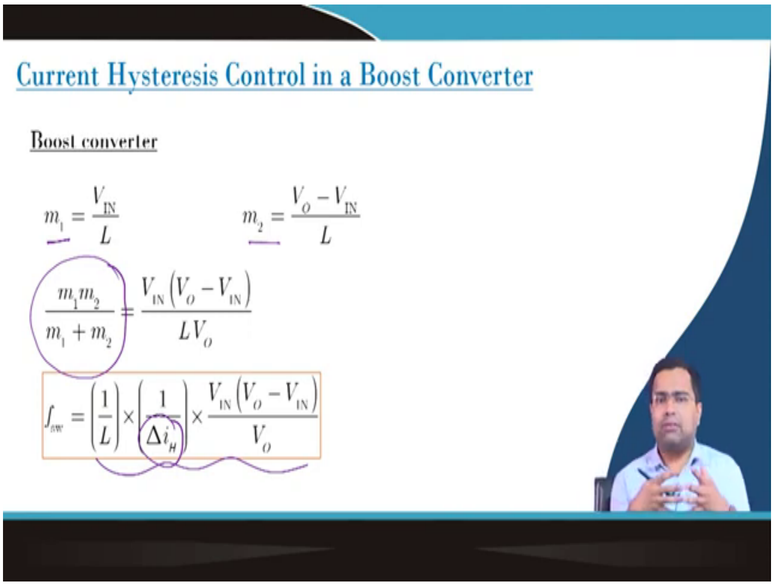

Under current hysteresis control for a boost converter, we know the rising slope, we know the falling slope and in our original expression we need to find out this m 1 m 2 by m 1 plus m 2. If you substitute then you can get the switching frequency which is again a function of input output voltage, hysteresis current and the inductance value.

So, if we want to regulate the switching frequency, the only parameter that is in our hand is the hysteresis band. If we adjust the hysteresis band, then we can keep the switching frequency constant or we can program it according to our requirement.

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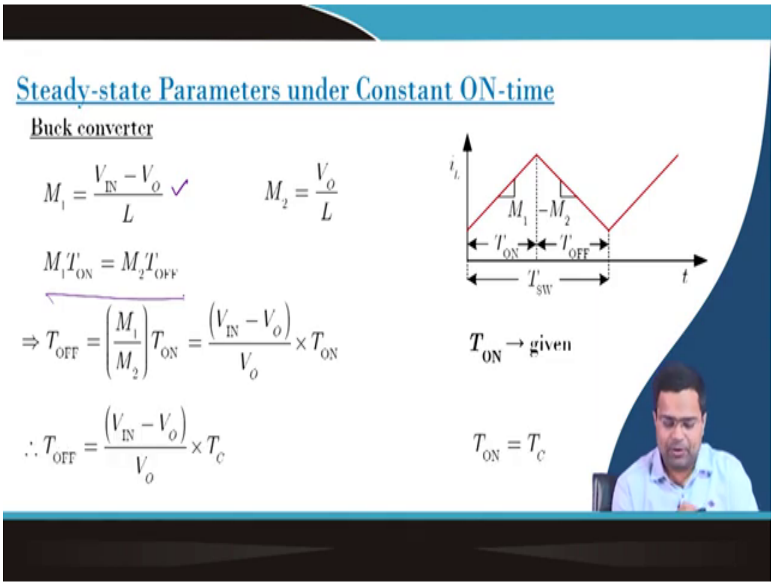

So, under buck converter, if you take the constant on time control, the rising slope is V IN minus V 0 by L falling slope. also you know we all this expression we have derived earlier.

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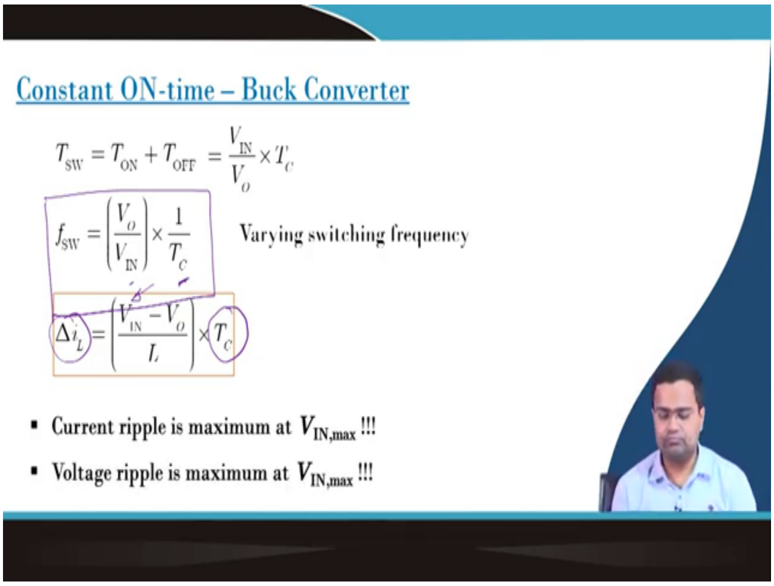

So, if we want to derive the inductor current ripple; that means, if we just the switching frequency can be derived from the voltage gain and it can be shown that under constant on time control the switching frequency is a function of voltage gain into 1 by T ON. So, if the on time is kept constant for varying input voltage switching frequency varies. If we take the ripple current, the ripple current expression shows that this is constant because, if we keep the on time constant.

So, in this expression, the inductor current ripple will be maximum when this input voltage is maximum. So, this part is consistent with the PWM, where we found the maximum current ripple is coming at highest input voltage. So, under constant on time this is also consistent, but here the switching frequency will vary.

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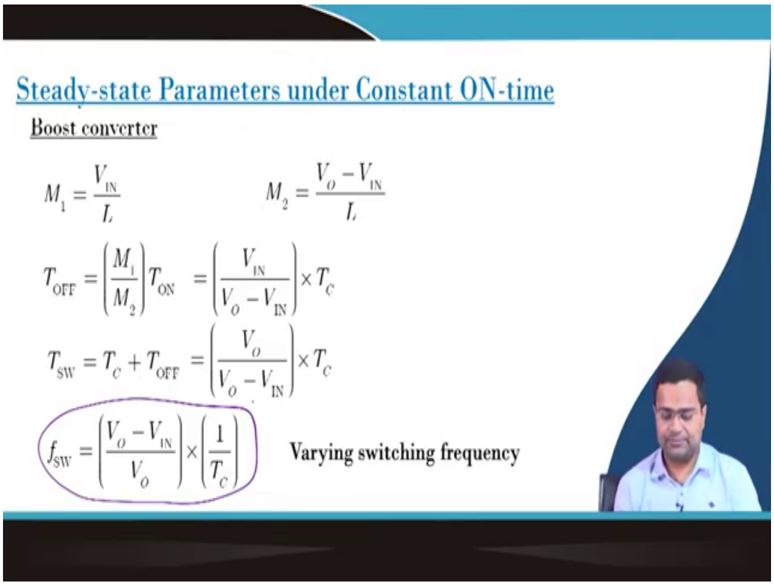

In a boost converter, if we derive this on time slope, off time slope and then if we derive the switching frequency, it is a function of input output voltage and the on time. So, switching frequency varies with the input voltage.

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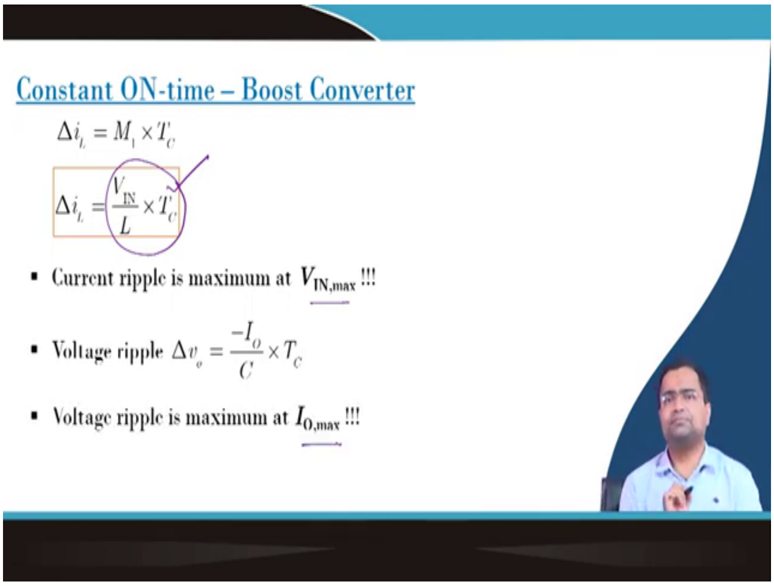

And if we take the Boost Converter current ripple expression, it can be computed that rising slope into on time. Since on time is constant, then you can see the current ripple for a given on time is maximum when the input voltage is maximum.

So, but in case of PWM we found the current ripple is maximum at 50 percent duty ratio. But here, under constant on time modulation, the current ripple is maximum at maximum input voltage. Output voltage ripple will be maximum at maximum load current.

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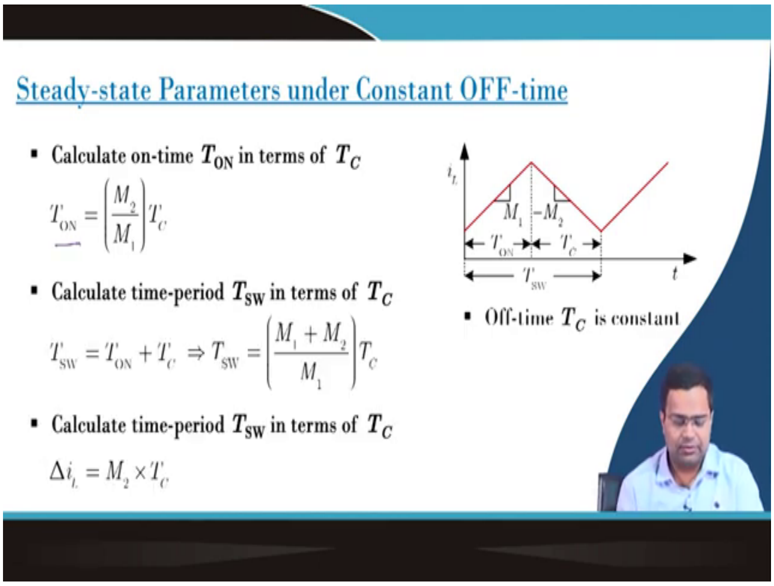

Again if we derive the Steady state Parameter under Constant OFF time control, since we have derived all this steady state parameter in my earlier lecture using timing parameter on time off time. So, you have to just replace this parameter and find out you know what are the like you know inductor current ripple, what is the inductor current ripple expression output voltage ripple expression and so on.

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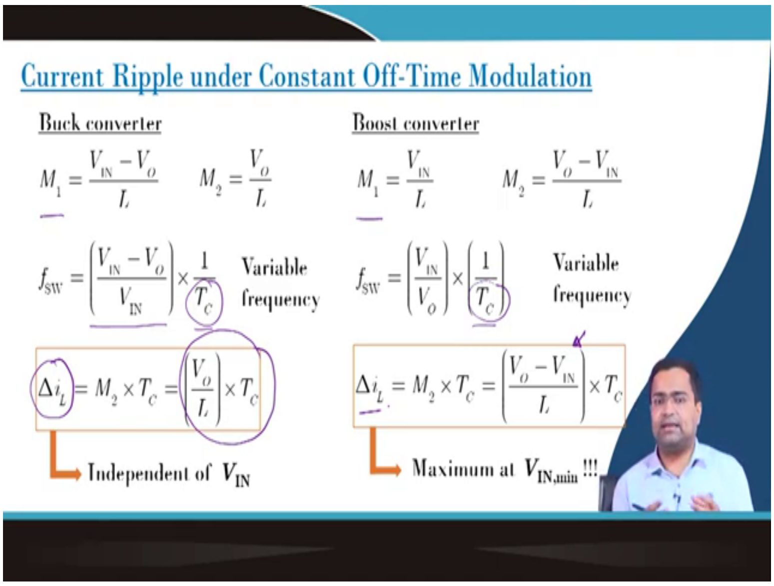

So, you can find out that T ON by computing all we are trying to find out the ripple current expression. So, for buck converter, the rising slope is this for Boost convertor is this we can also show the falling slope and the switching frequency is a function of input voltage and on time sorry here T C is the off time. And so switching frequency varies with the input voltage, but what is interesting to see the inductor current ripple for a buck converter it is independent of input voltage under constant off time modulation.

So, for constant off time the current ripple is insensitive to input voltage variation. Whereas for a boost converter, the current ripple is maximum when the input voltage is minimum; that means, at the highest voltage gain, you will get the highest ripple current. So, these expressions differ from pulse width as well as constant on time.

So, whenever we choose any of this technique we have to be very careful what is the worst-case design power stage design and that is why I wanted to show that under variable frequency modulation that ripple criteria and similarly you can find out the RMS calculation that already we have the equation. So, the power stage design need to be carefully considered when particularly you have to keep in mind which modulation technique are you going to use.

So, it is not the conventional technique that we use in PWM is equally applicable for constant on time off time it is not. So, you have to separately consider if you want to operate in constant on time, then what is the worst case, what is the worst case for constant off time and what is the worst case of PWM.

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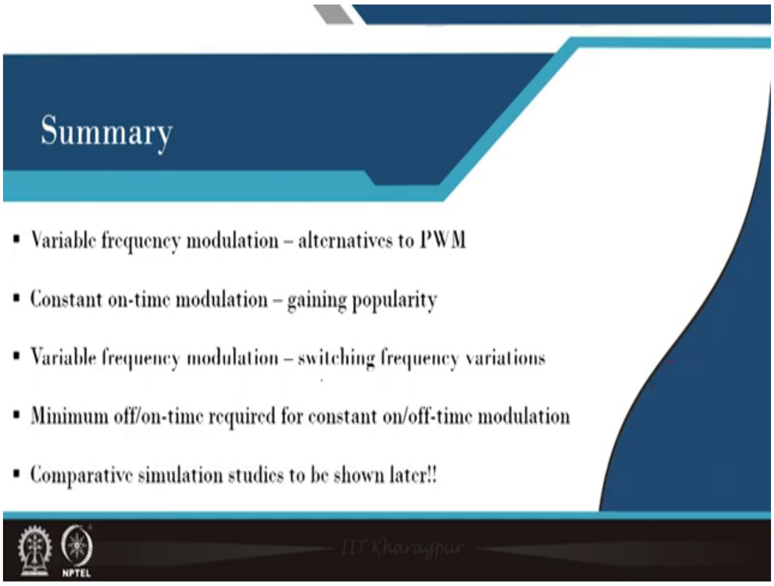

So, with this summary variable frequency modulation, we have discussed it is alternative to PWM constant on time modulation. Now this is you know this application is gaining more and more popularity, variable frequency modulation actually one of the problem is a switching frequency variation and minimum on time and off time is required for whether you take constant on time or constant off time modulation and then comparative simulation studies to be shown later. So, with this; this is the end of the today lecture.

Thank you very much