Power Electronics

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Lecture No. 15

Non-Isolated DC-DC Converters – I

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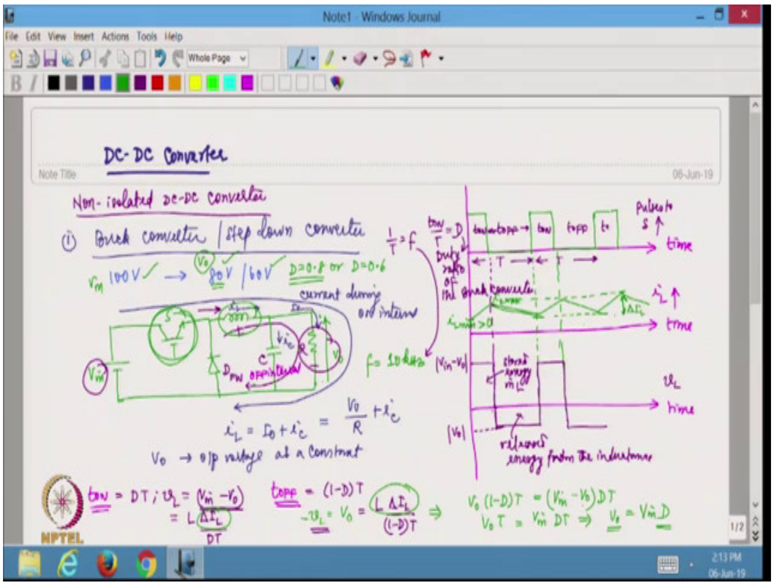

As I told you in the last class, we are going to take a look at DC to DC converters now and specifically non-isolated DC-DC converter and we will start with actually buck converter or step-down converter. So as the name indicates this is going to help us in stepping down the voltage, so let us say I have some 100 volts and I want to get it down to say 80 volts or 60 volts or something like that, I will be able do that using a buck converter.

So, the buck converter circuit look somewhat like this, let us say this is my V_{in}, I am going to have a switch S, I am showing this as an IGBT it could be a MOSFET, it could be a BJT but I am showing this as an IGBT here, so this is going to be my switch and I am going to have an inductance to smooth out the current then I will have a capacitance at the output to remove the ripple in the output voltage and then I am going to have a load I am showing the load as a resistive load and let me show this value as some R this is C this is L and I am going to have essentially this as the common ground.

Now, this is the diode which will incidentally work as a freewheeling diode, D_{FW}, which means if I am talking about this switch turning off, then I will have the current or inductance stored energy passing like this. Whereas when I am going to have the switch on it is going to essentially pass a current like this through the load, so this is essentially the current during on interval and this is going to be the path for the current during off interval, so these are the 2 parts in the current and one more thing I have to say is that if this is my inductance current which is i_L this is actually dividing itself into 2 parts, this is I_0 and this is going to be i_c so I should be able to write also that $i_L = I_0 + i_c$.

And the capacitance value is chosen very large so I am going to have V_0 which is the output voltage almost as a constant; because it is a constant, I can write this as

$$i_L = I_0 + i_c = \frac{V_0}{R} + i_c .$$

So, let me try to analysis this circuit with the mathematical equations that we are going to write for this, if I turn ON the device for some time that is known as the ON time or t_{ON}.

Similarly, when I am going to turn it off that particular interval is known as t_{OFF}, so let me draw the waveform simultaneously along with writing the equations as well. So, I am drawing everything with respect to time. So, all these are time axes, now let us say I am going to operate this at a frequency of a few kilohertz may be I will be just take it as 10 kilohertz this is going to be the operating frequency, what I mean by operating frequency is let us say I am going to keep the switch on for some time then it is going to be off for some time, again I am going to turn it on for some time and again I am turning it OFF for some time this is getting repeated. So, I am going to have this as t_{ON} this as t_{OFF} and again I am going to have this as t_{ON} and this as t_{OFF}.

Now, $t_{ON} + t_{OFF}$ put together counts for 1 cycle which is actually the period of the chopper, so this is going to repeat itself, so I would rather say $\frac{1}{T} = f$, which is the operating frequency of the chopper. Now, $\frac{t_{ON}}{T} = D$ is known as the duty ratio of the chopper or of the buck convertor, so in which from here I should be able to say $\frac{t_{ON}}{T}$ equals duty ratio which is actually D so t_{ON} will become DT, obviously t_{OFF} will be (1-D)T.

$$t_{ON} = DT \; ; \; t_{OFF} = (1-D)T$$

Now, let us try to write the equations for this particular chopper circuit. It is essentially chopping the voltage you can understand that whenever the switch is ON I am going to have this V_{in} connected to the load whenever the switch is OFF I do not have V_{in} connected to the load, so essentially the load voltage is chopped between V_{in} and 0, so this is essentially the pulses to the device S that is what I have drawn with respect to time.

Whenever I am going to have this particular device on, the inductance is getting the stored energy, this is going to get actually the energy supplied by V_{in}, so if I try to write what is V_L, voltage across the inductance that be V_{in}-V_0 but this is equal to $L\frac{di}{dt}$, so I can write this as L multiplied by whatever is the variation in the current or built up of the current divided by on time which is actually DT, this is the time duration.

$$v_L = V_{in} - V_0 = L\frac{\Delta I_L}{DT} \quad (1)$$

So, this is going to be the equation as far as the current in the inductor is concerned so I can show the current in the inductor is building up like this because I am having essentially a linear rate of rise in the current when I am going to turn off this switch I am going to have this as an open circuit so the current has to essentially circulate this through purple path.

So, this particular V_0 whatever is the voltage that is appearing that is coming in parallel with the inductance voltage, so I should be able to say $-V_L = V_0$, because inductance is not getting any energy it has to essentially give up whatever energy it has taken until now so the current will be coming down, this will be repeating itself in the next cycle as well, I am going to have the current increasing decreasing increasing decreasing and so on.

So, this is going to be changing from i_{Lmin} to i_{Lmax} and I can call this as the ΔI_L or whatever is the ripple in the inductance current, so what I have plotted here is i_L with respect to time, simultaneously I should be able to say what I have got as V_L if I try to plot what is the inductance value of voltage that we said as V_{in}-V_0 ,so that is essentially, let us say this is the value V_{in}-V_0, and when I am talking about t_{OFF} , so I am going to have essentially something like this as the inductance voltage.

$$-v_L = V_0 = L\frac{\Delta I_L}{(1-D)T} \quad (2)$$

So, you can see that the inductance voltage is going to have the waveform something like this, this magnitude being $|V_0|$, please note I am writing this as a magnitude and this is going to be $|V_{in} - V_0|$, so this corresponds to the stored energy in inductance that is same as the old second area similarly this will be the released energy from the inductance, from the inductance whatever is the energy that is available this is the released energy from the inductance.

And these 2 should be equal to each other, because inductance will not be able to retain any energy so I can say here $-v_L = V_0 = L\frac{\Delta I_L}{(1-D)T}$, so that is indicated by the fall in the current this is the fall in the current, so I am going to have the fall in the current somewhat like this.

Now, using these two I should be able to equate what is $L\Delta I_L$ in equation (1) to this $L\Delta I_L$ in equation (2) so I should be able to say $V_0(1-D)T = (V_{in} - V_0)DT$, let me take this V_0 times DT to this side so it will became $V_0T = V_{in}DT$ or I should be able to say $V_0 = V_{in}D$.

So, depending upon how much is the duty ratio I have for the switch if I am increasing D correspondingly my V_0 is going to increase, so initially I said from 100 volts I would like to obtain 80 volts or 60 volts, if I want 80 volts my duty ratio has to be 0.8 or if I want 60 volts the duty ratio has to be 0.6, so by varying the duty ratio I should be able to get a variable output voltage, so this is output voltage and this is the input voltage,

So, we are going to have variation in the output voltage as per the duty ratio that is the ON time of this particular switch. So far we have assumed that the inductance current is continuous that is $i_{L\min} > 0$ that is what we had assumed, so you can see that the circuit reaches steady state when $i_{L\min}$ is always at a particular value, similarly $i_{L\max}$ is always at a particular value, the current ripple is almost a constant under that condition we called it as steady state condition.

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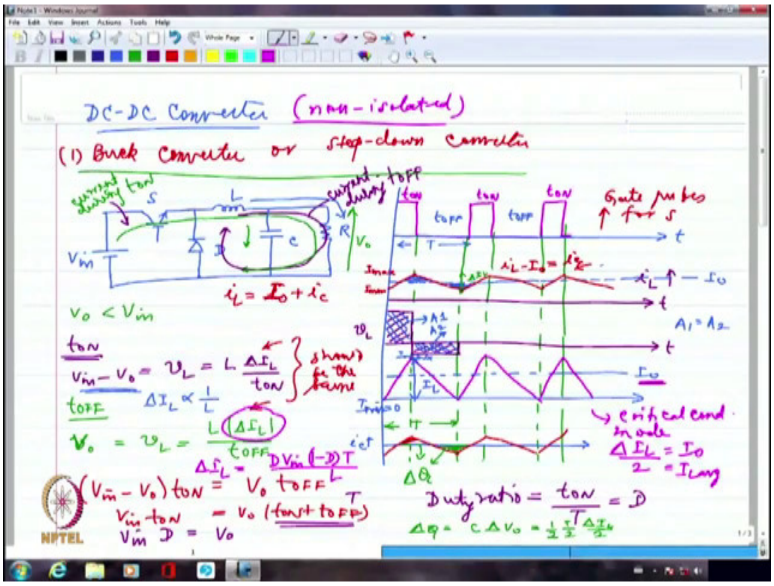
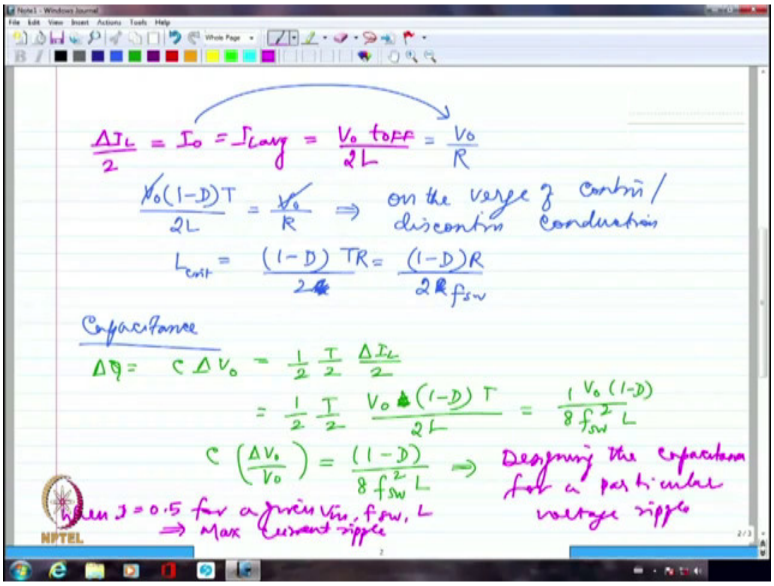




Now, if I look at the inductance current, the inductance current is always going through the load whether I like it or not the inductance and load are actually connected to each other all the time, but the inductance current is oscillatory whereas the load current is a steady value, so if I try to look at what is the average value of inductance current in all probability that will correspond to I_0 because capacitance might get charge sometimes it might discharge sometimes, capacitance will sometimes charge and sometimes discharge.

So, if my inductance current happens to be higher than the load current at that point the capacitance is going to take the extra current getting charged and whenever I am going to have the inductance current to be lower at that point I am going to see that the capacitance is pitching in so that it is meeting the demand of the load that is how it is going to be, so if I look at the average load current it will be somewhere here so whatever I get up and down that is this portion if I try to look at this is essentially the portion were the capacitance is accumulating charge and if I try to look at this portion this is where the capacitor is giving back its charge, both of them have to be equal to each other because the capacitance cannot accumulate charge in definitely.

So, whatever it is taking in it has to give out, so I will be able to calculate what is the capacitance value that I need to have if I do not want the ripple in the capacitor to go beyond the particular value of voltage. So this becomes essentially my design constraint if I want to have a design constraint regarding how much is the ripple I can allow in my DC to DC converter; this becomes my design constraint because how much is the charge accumulated that actually tells me how much will be the increase in the voltage or how much is the charge it is giving back that gives me what is the reduction in the voltage that I am going to get.

Now, one more thing we have to realise is that we have written the expression here,

$V_{in} - V_0 = L\frac{\Delta I_L}{t_{ON}}$, so if I try to look at how much is ΔI_L; $\Delta I_L \propto \frac{1}{L}$, so if I have lower inductance I will have more oscillation in the current if I have higher inductance I will have less oscillation in the current.

So, if I try to reduce the inductance further and further at some point the same current what is the average value of current I am still looking at the same average value of current let us say I_0 is my average value of current still but I will probably look at you know the oscillation becoming in such a way that it has gone all the way like this, this current and then it may again come down to 0 it may just touch down to 0 and then it will just go like this.

So, I am drawing the inductance current which may just touch 0 it not dwelling on 0 for too long what I am trying to get it is, let us say initially I started off with 100 μH, inductance, I reduced it to 90 μH, previously ΔI_L was may be 2 amperes, so maybe it was going from 4 ampere to 6 ampere.

Now, I have actually reduced the inductance from 100 μH to 90 μH then I am going to get it to 80 μH, when I am coming to 80 μH I may see a ripple of 3 amperes, so it may actually go from 3.5 or instead of 4 to 6 ampere now it may come to 3 to 6 ampere or 7 ampere, so I may have further and further increase in ΔI_L value.

So, I may come to a point of it is varying from almost 0 to 8 amperes if I bring down my inductance from 100 μH to probably 30 μH or 20 μH, so I can bring down my inductance in such a way that it just comes to the verge of continuous current to discontinuous current it had been continuous current because it was always above 0, so if I bring down the inductance further and further at some point it might just touch 0 value, if it touches 0 value like this that particular inductance value for that particular operating condition is known as the critical inductance value.

Critical inductance is that particular inductance value for a given operating condition were the current will just touch 0 and start rising again, so when it touches 0 it is not dwelling on 0 for too long, so this particular value is actually working as the threshold between continuous inductor current and discontinuous inductor current.

If, I try to go above this inductance value I will have continuous inductance current if I try to go beneath this inductance value, I will have discontinuous inductance current. So, this particular conduction mode is known as critical conduction mode and the corresponding inductance is called L critical or critical inductance.

So, let me try to calculate what is the critical inductance value for a buck convertor. If I am looking at this as the critical inductance value, so this is my I_0 and this is going to be the inductance value and we have assume linear rise so this should be the midpoint because it is a linear rise, I_0 has to be the average value which is also the midpoint of either if I assume ΔI_L is the total ripple in the current it will be $\Delta I_L / 2$; because it is the linear rise.

So, I should say under critical conduction mode, I am going to have $\Delta I_L / 2 = I_0$, I_0 is same as I_L average, because inductance current is always push through my load whether I like it or not they are always connected together.

Now, I can write from here let me just rewrite this again $\Delta I_L / 2 = I_0 = I_{Lavg}$ and we had return for ΔI_L an expression here ΔI_L I can write it as $\frac{(V_{in} - V_0)t_{ON}}{L}$ or I can write $\frac{V_0 t_{OFF}}{L}$ either way its fine, so let me write here,

$$\Delta I_L / 2 = I_0 = I_{Lavg} = \frac{V_0 t_{OFF}}{2L}$$

Now, I_0 is actually V_0/R, so I should be able to write this as,

$$\Delta I_L / 2 = I_0 = I_{Lavg} = \frac{V_0 t_{OFF}}{2L} = \frac{V_0(1-D)T}{2L} = \frac{V_0}{R}$$

This is in the case of on the verge of continuous and discontinuous conduction, that is under the critical conduction mode, this is true, which means I am going to say that,

$$L = \frac{(1-D)TR}{2}$$

where T is basically the period of the DC-DC Converter. So, 1/T =f so I should be able to write this as

$$L = \frac{(1-D)R}{2f_{sw}}$$, f_{sw} is switching frequency.

Critical inductance, $L_{crit} = \frac{(1-D)R}{2f_{sw}}$

This is known as the L critical value, but this is valid for a particular duty ratio, particular switching frequency and a particular load resistance, all of them definitely will decided what is the critical inductance. You should also realise that, this actually tells me that critical inductance value is inversely proportional to the switching frequency.

So, if I go for higher and higher switching frequency the inductance value I choose can be smaller and smaller because you are giving it very very smaller time really for charging or discharging, so you are not giving it ample time to go to a very high current or low current so the ripple will automatically decrease, so when you do not give the ample time for the current to increase or decrease then obviously I am going to have ripple to be small.

If, the ripple is small it is very unlikely that it might reach 0 current, because the average current is already chosen based on what is my resistance value, so higher the switching frequency smaller could be the inductance that is one reason why many of the DC-DC converters are operated at extremely large switching frequency so that the inductance values can become really really small and inductance is one of the most bulky components in many of the electrical circuits.

So, we tend to operate many of the DC-DC Converters at higher and higher switching frequency. One more major component that we need to design is the capacitance. I said basically that $i_L = I_0 + i_c$, so if I try to draw what is i_c I had to essentially draw this whatever I have drawn here in red in this portion that is actually the capacitance current but I should draw some portion above 0 some portion below 0.

So, I should look at this, like it is going like this then again it is going like this, this is how it is going to be. This is the capacitance current, please note I am drawing this itself only thing is instead of drawing it around I_0 I am drawing it around 0, because I_0 is going through this path and the parallel path is i_c and inductance current is the one what I have drawn here.

So, it is essentially $i_L - I_0 = i_c$, so this portion I multiplied by whatever is the time duration here that is essentially the accumulated charge in the capacitance and similarly this portion whatever is this current multiplied by this time duration will be the charge that is accumulated or given back by the capacitance both of them have to be equal to each other. Whatever is the accumulated charge, it should be given back by the capacitance.

So, that is what we are looking at us the negative current, negative current is giving back positive current is taking in, that is what happen, so correspondingly you should be able to draw the voltage variation although we are assuming it to be a constant the average value will be V_0 but it will have a small ripple definitely whenever it is taking in the current I will have increase in the voltage.

So, during this portion I will have increase in the voltage during this portion it will have reduction in the voltage, so again I urge you to simulate the circuit once in PSIM and take a look what kind of waveforms you are getting across each of the elements may be we will try to design one buck converter also and you take that value and put it in there no problem.

So, this is going to be the capacitance waveform, so I can write this is ΔQ that is the increase or decrease in the charge of the capacitance and this happens for half the duration here and half the duration here if I try to say this is totally T this is what is my T if I look at this, this will be half of t_{ON} this will be half of t_{OFF} because you are looking at essentially the current reaching in the mid value will be some were in the half of either t_{ON} or half of t_{OFF}.

So, if I look at this entire duration this will be half T basically, and also you know that this is ΔI_L, so hopefully whatever we are having as the peak of this triangle will be $\Delta I_L/2$ if I try to look at this as a triangle, then that will be $\Delta I_L/2$.

So, I can say ΔQ is area under this entire curve so $\Delta Q = C\Delta V_0 = \frac{1}{2}\frac{T}{2}\frac{\Delta I_L}{2}$ because I am looking at whatever is the ripple in the capacitor voltage. I am trying to write the area of the triangle half and base is T/2 and height is $\Delta I_L / 2$, we are looking at what is ΔQ value whether this or this we are looking at ΔQ value, that ΔQ value essentially will be whatever is my area of this triangle or this triangle it does not matter either of them will have the duration as $\frac{t_{ON}}{2} + \frac{t_{OFF}}{2}$ so that is T/2.

And the peak will be $\Delta I_L / 2$ because the total is I_L and in the middle whatever I am getting is the average value so it will be $\Delta I_L / 2$, so I can write now

$$\Delta Q = C\Delta V_0 = \frac{1}{2}\frac{T}{2}\frac{\Delta I_L}{2}$$

$\Delta I_L / 2$ if I try to write it in terms of whatever I have written for V_0 again, so I have written,

$$\Delta I_L = \frac{V_0 t_{OFF}}{L}.$$

So, this is

$$\Delta Q = C\Delta V_0 = \frac{1}{2}\frac{T}{2}\frac{\Delta I_L}{2} = \frac{V_0(1-D)T}{2L} = \frac{V_0(1-D)}{8f_{sw}^2 L}$$

So this is going to be $C\frac{\Delta V_0}{V_0} = \frac{(1-D)}{8f_{sw}^2 L}$ from which I should be able to calculate what is the capacitance value given my inductance value already switching frequency already and whatever is the voltage ripple that is allowed, if I am given this is the voltage ripple that is allowed then I should be able to definitely calculate this.

So, this gives me a way for designing the capacitance for a particular voltage ripple of course given switching frequency and inductance values and of course the operating condition because duty ratio also I have taken into consideration, so the operating condition is given already, you operate it at this particular duty ratio that is also given. One more thing may be which we would like to look at is, here I have taken t_{ON} to be much smaller as compare to t_{OFF}. If t_{ON} is also 50 percent and t_{OFF} is also 50 percent let us say in that case I am giving ample time for the current to rise and ample time for the current to fall look at it qualitatively basically.

If I give 50 percent time for the current to rise and 50 percent time for the current to fall, I am giving maximum amount of duration that can be given for rise and fall both are equal if I do not give sufficient time for the current to rise that is t_{ON} is much smaller then I am limiting how much could the rise in the current, on the other hand if I make the t_{OFF} to be much smaller then I am limiting how much current can fall really.

So, when I give equal amount of duration for the current to rise and fall I am maximizing the possibility of having a very large ΔI_L value, so normally the current ripple is maximum when the duty ratio is 0.5 that is actually the worst condition of current ripple this can be proven if you try to take probably one of this expressions either $\Delta I_L = \frac{V_0 t_{OFF}}{L}$ or $\Delta I_L = \frac{(V_{in} - V_0) t_{ON}}{L}$.

So, when will ΔI_L be maximum, V_0 can be written as, $V_0 = V_{in} D$, so I should be able to write this as, for example $\Delta I_L = \frac{D V_{in} (1-D) T}{L}$.

When will ΔI_L be maximum for this with respect to D you have to differentiate. You will get

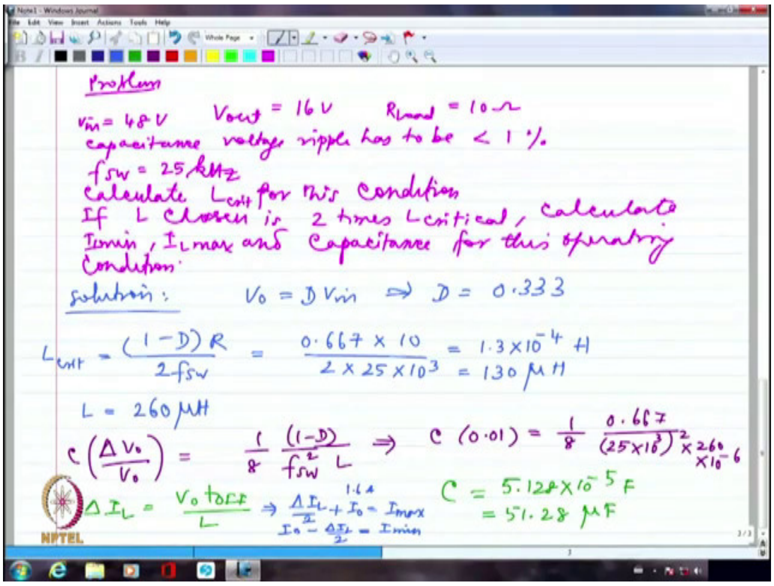
2D=1 which is D=0.5. Obviously, L is a constant I am not changing V_{in}, I am not changing L. Only thing I am trying to check is what happens to D.

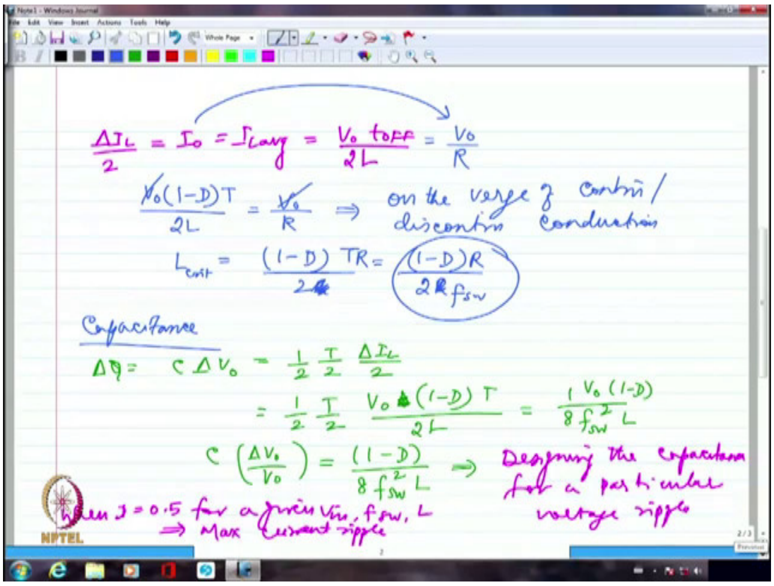
If I vary D at what point I am going to get maximum ΔI_L, so I will get 2D-1=0, so D will be equal to 0.5, so this is one more thing you should realize that when D equal to 0.5 for a given V_{in}, f_{sw}, L, C etc. I am going to have maximum current ripple, So D equal to 0.5 is the worst case scenario, if I want to make sure that I had to design some particular circuit for the critical conduction mode because under that condition if it does not touch down 0 then I know for sure that it will not touch 0 at any point in time, normally.

So, this is the worst case scenario, so, so much so forth for the buck converter under continuous conduction mode what I have seen is only inductance current is either continuous or it is going to touch just the 0 value it is not going to really dwell on 0 for longer because if it dwells on 0 for longer by chance if it is going to dwell on 0 for longer what I have taken as this, the volt second area what I have taken this equal to this that will not be valid because the current would come down to 0 the inductance is dead for some time and the load current is never going to be at a non-zero value at that point in time.

So, all these expressions whatever we have derived are valid only in continuous conduction region when I have continuous conduction through the inductance only in that region this particular thing is valid otherwise it will not be valid. So whatever we have drawn as the waveform are all in steady state, obviously inductance current cannot start from a non 0 value not at all, what we have drawn is all in steady state I have being running this particular circuit for ages that is all the more reason you should simulate and you should see first few cycles how it is really the current waveform and so on and so forth.

They will be definitely not steady state, initially for some time you would see that it is kind of I minimum and I maximum are not the same for consecutive cycles they will all change, because the inductance is still trying to come to steady state after going through some transience, that is the reason.(Refer Slide Time: 38:11)





Let us, probably try to do one problem for buck converter, I am not going to repeat this probably for every converter. So this is essentially V_{in} is 48 volts V_{out} what we want is 16 volts I have just arbitrarily taken values, load resistance I am going to take 10 ohm, capacitance voltage ripple has to be less than 1 percent, that is 0.16 volt, should be less than 1 percent of course we are talking about the output obviously because the capacitance is in the output side and switching frequency I am taking as 25 kilo hertz. Calculate L_{crit} for this condition.

Generally, if we derive the L_{crit} value when we actually implement it in hardware because of some variations that could happen in the construction of inductance and so on and tolerance in components we tend to take it as 2 times 3 times the critical inductance to ensure that we will get continuous conduction mode for all conditions of operation.

So, if L chosen is let us say 2 times L_{crit}, calculate I_{Lmin}, I_{Lmax} and let say a capacitance for this operating condition.

So, let us try to work this out, first of all you can definitely calculate what is the duty ratio because

$V_0 = V_{in} D \Rightarrow \quad D = 0.333$.

So once I have this and if I have switching frequency I can definitely calculate what is L_{crit} because I have got R value also, let us look at the expression

$$L_{crit} = \frac{(1-D)R}{2f_{sw}} = \frac{0.667\times 10}{2\times 25\times 10^{3}} = 1.3\times 10^{-4} H = 130\mu H$$

So, you can do a little bit of checking up if you increase the switching frequency obviously to 50 kilo hertz you are going to have much lower, half of this.

So, you are as you increase the switching frequency the inductance value comes down further and further for the same operating condition, let us assume twice this value as the L value, so I am going to have,

L = 260 μH, so you should be able to calculate first of all say capacitance value which we have again written the expression

$$C\frac{\Delta V_0}{V_0} = \frac{(1-D)}{8f_{sw}^2 L}$$

$$C(0.01) = \frac{1}{8}\frac{0.667}{(25\times10^3)^2\times260\times10^{-6}} = 5.128\times10^{-5}F = 51.28\mu F$$

Any way you can check it up.

So, this is the kind of capacitance value we are getting again we may put a slight factor safety or you might like to round it off because when we make the design generally we will not get 51.28 μF from the market, it is not possible, whatever is the closest value but a little higher value, because we need to adhere to $\frac{\Delta V_0}{V_0}$; we do not want to violate that, that is important.

So, that is the reason why we will choose something closer to this whatever is available in the market not 47 μF which will be definitely available in the market, so whatever is the next available value we will try to choose it, that is what we will do, how will you calculate I_{Lmax} and I_{Lmin}? We have an expression already, ΔI_L you can definitely calculate an you know what is the average value.

So, ΔI_L once you calculate, I_0=16/10=1.6 A, so, $I_{Lmax} = I_0 + \frac{\Delta I_L}{2} = 1.6 + \frac{\Delta I_L}{2}$ and $I_{L\min} = 1.6 - \frac{\Delta I_L}{2}$, as simple as that, so you should be able to calculate I_{Lmax} and I_{Lmin}

So, ΔI_L can be calculated as $\Delta I_L = \frac{V_0 t_{OFF}}{L}$

L value we have chosen V_0 we know t_{OFF} we know because $t_{OFF} = 0.667\times\frac{1}{25\times10^3}$.

I cannot have I_{min} less than 0, if in the problem if you get I_{min} less than 0 that means you have gone into discontinuous conduction mode it is not continuous conduction mode any more, that is what it means. For some kind of design values, if you are getting I_{min} to be less than 0, DC-DC Converter cannot have current in the reverse direction, please understand that.

So, if I am getting less than 0 that means I have entered into discontinuous conduction mode of current, I have still not ventured into discontinuous conduction mode what I am thinking is I will first complete the continuous conduction mode for all the 3 DC DC Converters then I will venture into discontinuous conduction mode just like what Daniel Hart has done the same way.

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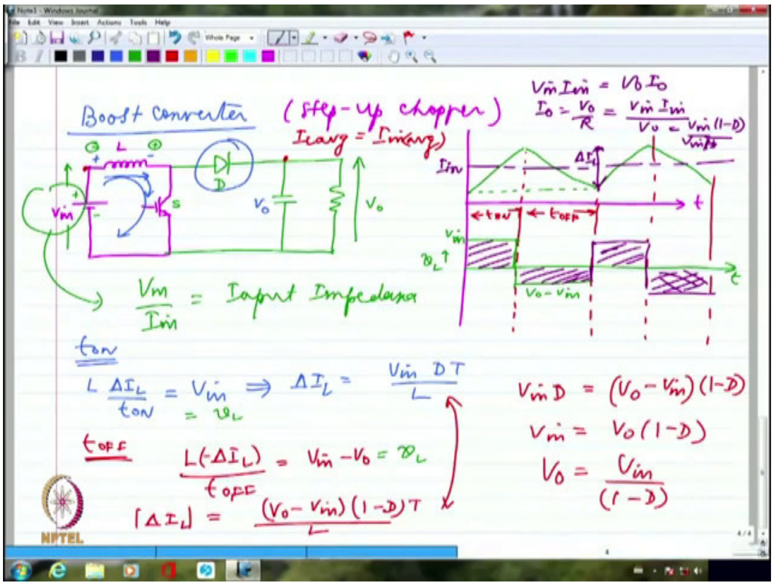

So, now please use these values try to simulate your buck converter and see the waveforms of different components voltages and currents see how they look, definitely you will see a voltage ripple in the output also, definitely you will see but that is only within 1 percent which we are ignoring as simple as that. Now, let us go over to boost converter which is a step-up chopper or step up converter.

Chopper is another name used for DC to DC Converter, so I am just using the word chopper also and chopper is generally not used for isolated converter, it is only for non-isolated. As I told you all these converters are going to have the resistance load L, C, diode and a switch, in the boost converter I am having an input voltage, but I want the output voltage to be more than the input voltage for which I will actually store energy in an inductance.

So, I am going to have an inductance in series, so I am going to have this having some energy stored by having a switch here, so whenever I turned the switch on, the inductance is short circuiting the input voltage, and normally inductance when you connect it across a DC supply it is a dead short, if you allow it to continue for too long, the current can go to infinity but we are not going to continue it for too long because you will normally operate it at much higher frequency and we will have definitely a duty ratio.

So, we are going to turn it on only for a short while and when I am turning it on, my inductance is going to carry a current like this, in this direction through the switch, so I will have plus here and minus here when it is carrying a current through the switch so it is going to carry a current like this. After a while I am going to turn off the switch when I turn off the switch the inductance has stored energy and it has to find a path to you know kind of discharge itself or give back its energy.

When it will give back its energy this will become minus and this will become plus and I have minus here and plus here, so they become additive. The inductance voltage gets added to whatever is my input voltage and I will put a diode here which will get forward biased if I add both these voltages together because of which it is going to pass on the energy to a resistive load of course I will put a capacitance for reducing the voltage ripple. The capacitance is only mainly working as a filter.

So, this diode actually is not going to work initially until I have the switch ON when S is ON I am not going to have the D conducting but once I turn off S, the inductance will find a path to discharge itself or give back its energy by actually forward biasing the diode, so this is going to be V_0 and this is V_{in} and in this particular case if I assume again diode is not going to have any drop if I neglect the drop across the diode I am going have essentially whatever is the voltage that is actually coming across the inductance when it is discharging its energy plus V_{in} is going to become V_0, so V_0 happens to be greater than V_{in} because of that reason.

Because V_{in} plus V_L especially when inductance is giving back its energy that will become V_0, so V_0 happens to be greater than V_{in}. So this is the basic principle of operation of the boost converter, so without having an inductance boost converter will not work I will definitely need an inductance you cannot make a boost converter without an inductance and the inductance becomes a very very important component here, because that is the one which is doing the boosting action and that puts a limitation of how much of boosting I will be able to do from in V_{in} to V_0 generally we will not be able to do more than 2 to 3 times in most of the cases.

But there have being additional inductors and interleaved inductor I may have 2 inductors which are having mutual coupling and things like that, I may have multiple inductors like that and people have achieved around 10 to 20 as the boosting ratio that is V_0/Vin they have achieved until 10 or 15 or 20.

So, these are extensively used in solar PV generating systems boost converters are extensively used in solar PV because most of the times what solar PV generates will be a very very small amount of voltage although you may connect many of them in series still you may get only about 200-230 volts and that is under the best possible operating condition and in a place like Delhi were you are going to have huge amount of temperature variations you will definitely have much more drop in the voltage in the summers.

Because when the temperature increases the voltage will normally drop open circuit voltage will also drop for a solar PV, so you need to have most of the time some boost converter to make sure that the voltage is boosted to appropriate value so that it can be connected to the load and the load requirement will be met only if you have a boost converter.

And one more reason boost converter is used is maximum power that need to be harvested from the solar PV you need to create a situation as though the resistance that is post to the solar PV looks at the operating point which is corresponding to maximum power, so which means I may have a resistance of 10 ohm but please remember V_{in}/I_{in} is the input impedance that this source will be visualizing.

The source will be visualizing and input impedance of V_{in}/I_{in} but what I connect as the resistance is V_0/I_0 and V_0/I_0 will not be equal to V_{in}/I_{in} it is like a transformer ratio, in transformer you have that turns ratio coming to picture all the time, so you will not have R_0 same as R_{in}; R_{in} can be adjusted appropriately by adjusting the duty ratio.

So, boost converter plays a vital role in adjusting that R_{in} by adjusting the duty ratio for a given load such that the solar PV believes what I am getting as the load is at my maximum power, so let me deliver the maximum power that is way the entire system works. So, now let us try to take a look at the boost converters working basically by equations, so if I am having the switch ON, at that point I am going to have $L\frac{\Delta I_L}{t_{ON}} = V_{in}$, because there is no other resistance in the circuit only thing that is going to happen is this portion is going to work that is it.

If at all the load has to get a current the load has to get a current only from the capacitance stored energy nothing else. The input side is completely isolated from the output side because the diode is not conducting now, so R and C is becoming one circuit separately and you are having one more circuit with input voltage inductance and the switch.

So, there are 2 distinct portions and this is not conducting, this diode is not conducting, so there is no interconnection between the input and output portion, so this is going to be the ΔI_L value so I can write $\Delta I_L = \frac{V_{in}DT}{L}$, so if I try to draw the inductance current during this particular duration it is going to increase somewhat like this may be from some value it will increase like this.

So, I am calling this duration as t_{ON}, now after that I am going to turn off this particular switch S, so that is turned off so I am going to have the inductance actually delivering the energy through the diode to the load and may be part of it will also go toward charging the capacitor does not matter.

So, when the inductance is delivering its energy obviously the current will start coming down, so I am going to have the current coming down to the same value, again this will increase if I have t_{ON} then it will come down and so on, so this is going to be t_{OFF}, so this will repeat itself and please note in this particular case the input side current becomes the inductance current as it oppose to in the buck converter we had the inductance current was my load current whereas here my inductance current happen to be my input current Iin not Io.

So, in this case I should say $I_{Lavg} = I_{inavg}$, inductance voltage is getting added to the battery so I have to write very clearly during t_{OFF} I have to write

$$\frac{L(-\Delta I_L)}{t_{OFF}} = V_{in} - V_0$$

So, this becomes my second equation which is corresponding to my switch being in off condition, so I have to look at the difference between these 2 voltages, this is V_0 and this is V_{in} that is equal to V_L and V_L very clearly is now in the opposite sense because of current coming down so that is the reason I have written it like this, so I should write basically in this case,

$$\left|\Delta I_L\right| = \frac{(V_0 - V_{in})(1-D)T}{L}$$

So these two have to be equated, so we will say $V_{in}D = (V_0 - V_{in})(1-D)$

So, $V_{in} = V_0(1-D) \Rightarrow \quad V_0 = \frac{V_{in}}{(1-D)}$

Which will tell me as though if my D is 1, literally I have to get V_0 equal to infinity, but I am not going to give a chance for the inductance to release its energy at all. If D is 1 that means I am continuously having my switch ON, I am never turning it off when will I give the chance for the inductance to release its energy.

So, the inductance will keep on getting further and further energy so does not make much sense, so do not look at only as a simple mathematical equation look at it a little physically whether it will really work with D equal to 1, it will not really work with D equal to 1 properly which means it is going to be on for all the time and the inductance will not be able to release its energy at all.

So, if this is my inductance waveform, let me try to look at what happens to the inductance voltage, what we just now wrote let us try to write that. Draw that in the form of waveform, so we said that this is actually V_L similarly this is actually V_L, so during ON time my inductance voltage is going to be V_{in} so this is V_{in} and during off time it is going to be V_0-V_{in}, that is why I have drawn it in the negative side.

So, again this area whatever I see here which is the volt second area of the inductance during on duration has to be equal to the volts second area of the off duration, both of them have to be equal to each other because the inductance will not able to retain any energy with its own cell within one period whatever it takes it has to give back and it has to come back to the original state at the end of that one period.

So, this will repeat itself like this, this area and this area should be equal to each other, now if I try to draw again the average current what I get so this is my ΔI_L, current ripple, and the average current is I_{in} whatever is my I_{input} current that will be the average inductor current as well, so I_{in} whatever I get I should be able to say the overall power is V_{in} multiplied by I_{in} and if assume a lossless converter I will get V_0 multiplied by I_0 from which I may be able to arrive at a relationship between inductance current and I_0.If I write

$$V_{in}I_{in} = V_0 I_0$$

$$I_0 = \frac{V_0}{R} = \frac{V_{in}I_{in}}{V_0}$$

,Vo is $V_0 = \frac{V_{in}}{(1-D)}$ so I will have cancellation of those 2 V_{in} directly, I can write this as

$$I_0 = \frac{V_0}{R} = \frac{V_{in}I_{in}}{V_0} = \frac{V_{in}I_{in}(1-D)}{V_{in}}$$

I_{in} I can write that as $I_{Laverage}$,I should be able to write that as I_{Lavg}, from which I should be able to write the whole thing in terms of the critical conduction mode and arrive at an expression for L_{crit}.

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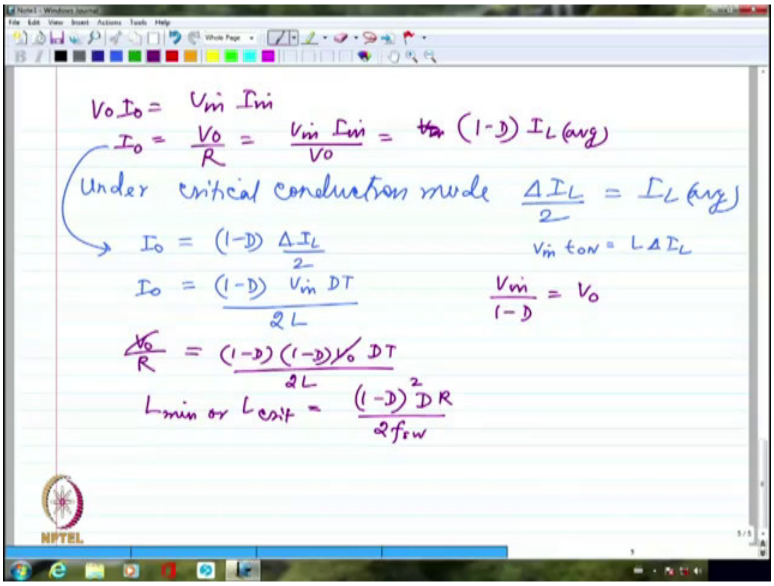

So, let me write this, $I_0 = \frac{V_0}{R} = \frac{V_{in}I_{in}}{V_0} = \frac{V_{in}I_{in}(1-D)}{V_{in}} = (1-D)I_L(avg)$

Now I can say under critical conduction mode $\frac{\Delta I_L}{2} = I_L(avg)$

So, I can write $I_0 = (1-D)\frac{\Delta I_L}{2}$

ΔI_L expression I have two of them, $V_{in}t_{ON} = L\Delta I_L$ this is for on instant and for off instant also we wrote one more thing I can used this expression itself if I want to, it should not be problem, so I can simply write

$$I_0 = (1-D)\frac{\Delta I_L}{2} = \frac{(1-D)V_{in}DT}{2L} = \frac{(1-D)(1-D)V_0DT}{2L} = \frac{V_0}{R}$$

so I should be able to write L minimum or L critical

$$L_{\min} \text{ or } L_{crit} = \frac{(1-D)^2 DR}{2f_{sw}}$$

I hope I have done it correctly any way we will verify it once again.

So, this is the critical inductance value for your boost converter if I try to go above this value under this operating condition I will get continuous conduction if I try to go below this value will have discontinuous conduction, so we will continue with the boost converter in the next class I would like you guys to please do some simulation look at the waveforms so that the concept gets reinforced, Thank you.