Power Electronics
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Lecture 16
Non-Isolated DC-DC Converters-2

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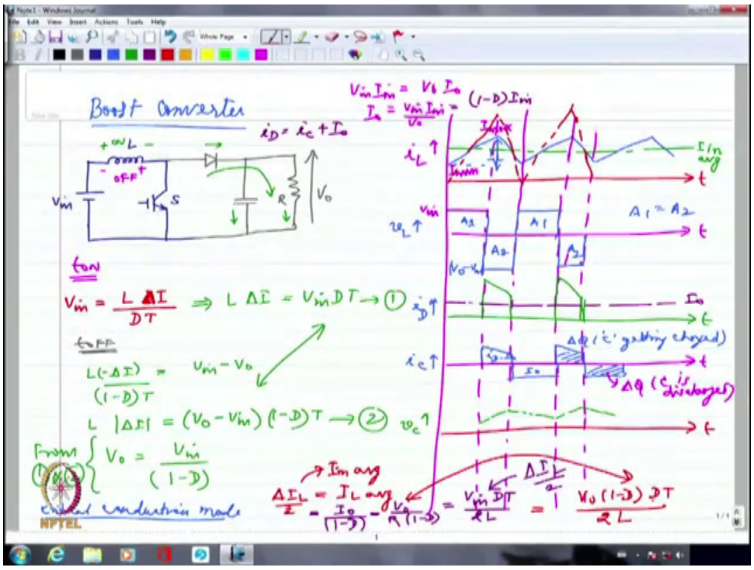

We had started on boost converter the other day and I had just written the basic configuration of the boost converter we have still not drawn the waveforms, so I said basically you are going to have a V_{in} and then you are going to have an inductor which is trying to store energy. When I have this particular switch S being closed. So when the switch is closed, if you assume it is ideal switch and ideal inductor, the entire energy that is the voltage that is being applied is going towards increasing the current in the inductor.

So, I will have during t_{ON} interval, I am going to have $V_{in} = \frac{L \Delta I_L}{DT}$ This is going to be the equation as far as the ON time is concerned. Now after this you are going to have actually a diode connected like this and a capacitor connected in this particular direction and I am going to have a load connected here. And we are going to have actually the inductance stored energy which is actually being released during OFF interval its voltage comes in series with the voltage that is input.

So, V_{in} plus whatever is V_L both of them come together in series addition because of which V_o actually is a large value, so we are going to have $V_0 > V_{in}$ because of the inductance stored energy.

So during t_{OFF} if I write the equation I should have actually during this particular interval I am going to have the inductance during the OFF interval, I am going to have the inductance having minus here and plus here, this is going to be the case during OFF interval that is when I am going to have a switch OFF.

Whereas when the switch is ON, I am going to have it the other way around, I am going to have this as plus and this as minus when the switch is ON. So, we are going to have during OFF interval,

During t_{ON}:
$$L\Delta I_L = V_{in}DT \tag{1}$$

During t_{OFF}:
$$\frac{L(-\Delta I_L)}{(1-D)T} = V_{in} - V_0$$

$$L\left|\Delta I_L\right| = (V_0 - V_{in})(1-D)T \tag{2}$$

we equated these two equations (1) and (2), that is what we did because the increase in the inductor current has to be equal to the reduction in the inductor current.

So, we can say basically that, $V_0 = \dfrac{V_{in}}{(1-D)}$ This is what is the expression for this particular input–output relationship.

Let us try to draw the waveforms. I am trying to draw the waveforms for this converter. We started off with inductor current if you may recall, so let me draw this as t so we had the inductor current increasing and may be decreasing and again increasing, decreasing, again increasing, decreasing and so on. This is the way the inductor current was. Why we are taking this current as linear? One is we are neglecting whatever is the resistance that is coming along with the inductance and second thing is the rate at which the inductance is being switched on and switch OFF.

The switch is being switched on and switch OFF is very much higher as compared to the time constant. So for a short time period we can assume it to be fairly linear, so that is the reason why we are assuming it to be linear because the switching frequency is normally assumed to be much higher than the time constant of the inductance itself. So it will definitely not reach a constant value eventually, we will not allow it to reach a constant value still increasing and that too linearly that is what we are trying to say.

So I will have to draw this time interval, so this is going to be one of the time intervals which is corresponding to say DT and the next one is going to be corresponding to the end of the period T. So, this is actually my i_L value and it is starting from whatever is my I_{min} and reaching I_{max}, so I can say this is actually my ΔI_L value until here, this is ΔI_L value. Now if I look at the inductance voltage during this interval, when I am actually turning it ON, the switch is turned ON V_{in} whatever is the input voltage that is coming across the inductance.

So, during the ON interval I should show it as though I am going to have V_{in}, if I say this is V_{in}, so I am talking about what is the value of V_L? V_L waveform I am drawing, so this is V_{in}. And then I am looking at actually the OFF interval, I will have whatever is $V_0 - V_{in}$, in the reverse direction, so that is the reason why we are drawing it in the negative direction. So, this is going to be say $V_0 - V_{in}$ magnitude, that is coming at the inductance voltage during the OFF interval.

Very clearly, if I call this area 1 as A_1, and this as A_2 (area 2), A_1 and A_2 had to be equal to each other because the inductance cannot retain any of its energy for the entire cycle, whatever it is taking it has to come back to its original state at the end of that one cycle. So, if I actually look at this area, if I just try to draw this entire thing again for the second cycle as well, so this is corresponding to ON interval and this is the OFF interval. So I am going to have again this as say A1, and A_2 has to be exactly equal to A_1.

So A_1 and A_2 have to be equal to each other so that the inductance does not retain any energy. So we are talking about again steady state operation like what I said, I am not taking as though the circuit was completely dead and I have turned it ON, because if I do that, definitely inductance will take a while before it accumulate some energy. So this is going to be the waveform for inductance, inductance voltage. Now let us try to take a look at what is the kind of input current that I am going to have? Please note that now the inductance is connected on the input side, just like how it was connected on the outside as far as buck converter was concerned.

So, whatever was I_L average in the buck converter it was I_o, whereas here I_L average is going to be I_{in}, whatever is the input current. So if I try to look at what is the average current here maybe somewhere here this is the average value, this is going to be I_{in} average which is also same as I_L average. So I_{in} average and I_L average are essentially one and the same. But if I look at what is the load current, the load current is essentially whatever is the current that is flowing through the resistor very clearly during the on interval, the supply has nothing to do with the load.

Because it is essentially being short circuited through the inductance with the switch. There is no question of the supply getting connected to the load at all. So if the capacitance is having some stored energy that is going to retain the load current. Whereas if I try to look at the OFF interval, the inductance is actually driving the current through the diode and it is going to actually drive the current through both these. The capacitance whatever it had lost during the on interval of the switch it will try to replenish during the OFF interval of the switch because the inductance stored energy is coming to the load along with that the capacitance is also getting some amount of the stored energy.

So, the capacitance is going to get charged during that particular interval, so if I say this is t, again if I try to draw what is the diode current, diode will not have any current during OFF interval, so during ON interval whatever is my inductance current that is going to come up as the diode current. So, I should say this is what is the diode current. This is going to be the diode current. So, the diode current comes up only during the OFF interval of this entire cycle. If I try to look at it for 1 cycle only during the OFF interval, I will get the diode current.

And if I look at the diode currents average, then I am going to get something like this as the average. Probably this is going to be the average, and this average is actually I_o, because whether I like it or not, the load current has to continue, we are assuming that the load has to be supplied continuously and we assuming output voltage is V_o. So I need to get continuous current in the load and that is essentially being possible by the capacitance stored energy.

So, the capacitance is going to give the current during the OFF interval and otherwise it is going to during the ON interval and otherwise the inductance is going to release its stored energy. So if this is I_o and this is diode current, I can write here, $i_D=i_C+I_0$. So because of which I should be able to write clearly what is the capacitance current. So I can draw that the capacitance current is somewhat like this, I am going to get some portion like this which is probably the diode current and some portion like this which is I_o.

This is actually this is i_D - I_o. So, I will have this repeating cycle after cycle. So, I am going to have something like this and then again something like this as my i_C if I try to draw. This is i_D, what I have drawn here is the diode current. So this particular portion is what is actually given out by the capacitor whereas this is what is gained by the capacitor. So, I should say this is ΔQ which is actually capacitor getting charge. Whereas this is ΔQ where C is discharged, or it is getting discharged through the load.

So I should have these two equal to each other, because the capacitor if I have some net charging or net discharging, the voltage will keep on going down or it will have increase in the voltage. So, if I assume that the voltage is fairly a constant this ΔQ has to be equal to whatever it has gained it should be giving back also. So whenever it is gaining if I try to look at what is the kind of capacitance voltage, so the capacitance voltage should be increasing whenever it is gaining charge and it should be decreasing whenever it is giving back the charge, this is how it should be.

So this will be whatever is my V_C value. So the capacitance voltage will essentially increase and decrease, but we want that to be within the limit whatever we have specifying and that is how we design the capacitor value, we arrive at the capacitor value. So first of all to arrive at what is the minimum value of inductance to maintain continuous current, continuous inductor current. So let us try to look at first of all critical conduction mode. So let us say I am decreasing the inductance further and further, clearly, I am going to have more and more ripple in the current.

So the current ripple might increase and maybe I will have a waveform something like this, it may go from here and reach very high value here and come down, and then, again, go from here reach very high value and come down. So this is essentially showing the case where the inductance have been decreased quite a bit, under what condition I am going to have that just touching 0 value. So, this is actually going to $\frac{\Delta I_L}{2} = I_{Lavg}$.

Under this condition and I_L average this is also same as I_{in} average and we know that if it is a lossless converter, I can write

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

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

$$\frac{\Delta I_L}{2} = I_{Lavg}$$

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

$$\frac{V_0}{R(1-D)} = \frac{V_0(1-D)DT}{2L}$$

$$L_{\min} = \frac{(1-D)^2 DR}{2f}$$

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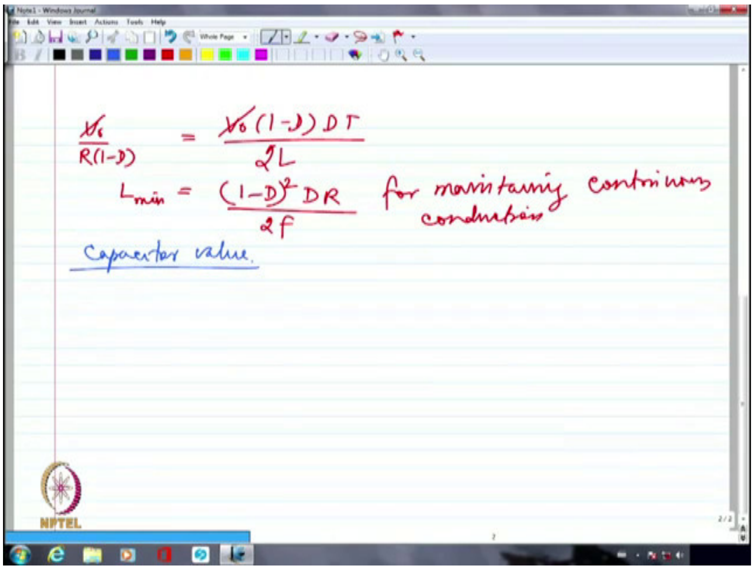


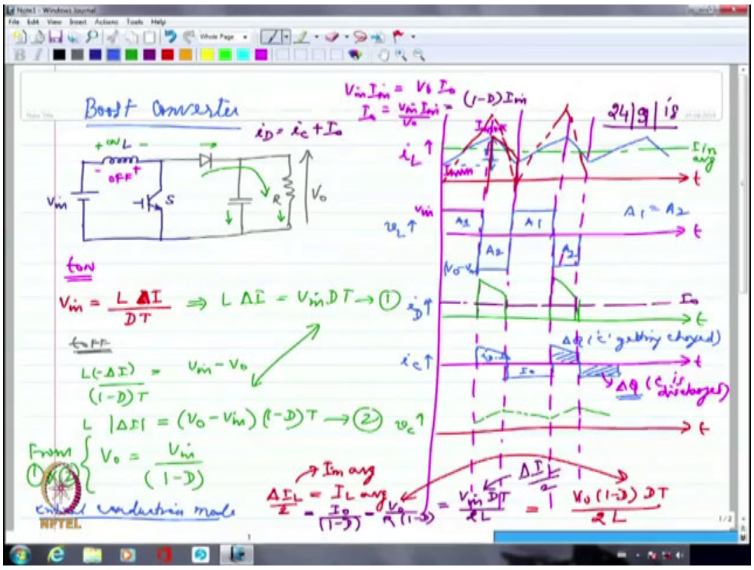
$$\frac{\cancel{V_0}}{R(1-D)} = \frac{\cancel{V_0}(1-D)DT}{2L}$$

$$L_{min} = \frac{(1-D)^2 DR}{2f}$$ for maintaining continuous conduction

Capacitor value.

So this is the expression for the minimum inductance for maintaining critical conduction or continuous conduction, just continuous conduction. What I mean is the current will jut touch 0 and then it will go from there again it will increase. So if it the inductance happens to be greater than this value, it will be continuous conduction if the inductance happens to be lower than this value, it is going to be discontinuous conduction.

Now if this is all for this particular duty ratio, this particular resistance and also for particular frequency. So if I increase the operating frequency, my inductance can come down. So higher the operating frequency, again, smaller the inductance same as what we talked about in the case of buck converter. Now we are yet to arrive at capacitor value, we have to arrive at the capacitor value. So whatever we actually drew as the waveform corresponding to capacitance current, we can try to get the expression for ΔQ.(Refer Slide Time: 20:57)



Boost Converter

24/9/18

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

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

$i_D = i_c + I_0$

t_{ON}

$V_{in} = \frac{L \Delta I}{DT} \Rightarrow L \Delta I = V_{in} D T \rightarrow ①$

t_{OFF}

$\frac{L(-\Delta I)}{(1-D)T} = V_{in} - V_0$

$L |\Delta I| = (V_0 - V_{in})(1-D)T \rightarrow ②$

From ① & ② $\left\{ V_0 = \frac{V_{in}}{(1-D)} \right.$

critical conduction mode

$\frac{\Delta I_L}{2} = \overset{\rightarrow I_{in\,avg}}{I_{L\,avg}} = \frac{I_0}{(1-D)} = \frac{V_0}{R(1-D)} = \frac{V_{in} DT}{2L} = \frac{V_0 (1-D) DT}{2L}$

Clearly getting this ΔQ is easier. Because I have a rectangular area so it is much easier. So, if I try to get the area of this particular ΔQ it is actually I_0 is the value and what is the time duration? Time duration corresponds to on time, so it is DT.

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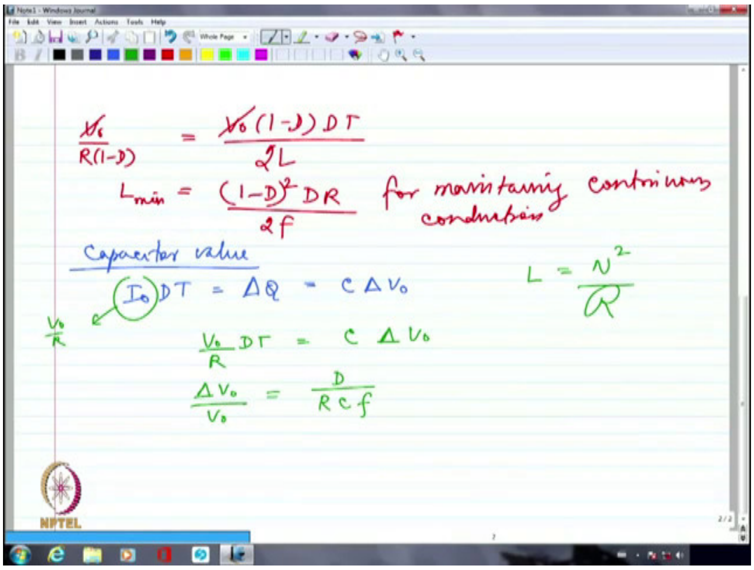

$$\frac{\cancel{V_0}}{R(1-D)} = \frac{\cancel{V_0}(1-D)DT}{2L}$$

$$L_{min} = \frac{(1-D)^2 DR}{2f}$$ for maintaining continuous conduction

Capacitor value

$$\boxed{I_0} DT = \Delta Q = C\Delta V_0$$

$$\frac{V_0}{R}$$

$$L = \frac{N^2}{\mathcal{R}}$$

$$\frac{V_0}{R} DT = C \Delta V_0$$

$$\frac{\Delta V_0}{V_0} = \frac{D}{RCf}$$

So I should say

$$I_0DT = \Delta Q = C\Delta V_0$$, whatever is the ripple in the voltage

$$\frac{V_0}{R}DT = C\Delta V_0$$

$$\frac{\Delta V_0}{V_0} = \frac{D}{RCf}$$

So this actually is giving me whatever is the capacitor design for arriving at the particular value of voltage ripple, the voltage ripple has to be within that particular value so then you will be able to get this. So, in the case of boost converter, one of the limitations what we have, as I mentioned in the last class, is the inductance value to which I can design it. So in most of the cases where it is a very high power system, large power configuration it becomes extremely difficult first of all to design an inductance value corresponding to very large current, as well as a larger value.

Please understand if I want the inductance value to be larger, you guys must recall what you studied in magnetic circuit, $L = \frac{N^2}{R}$. So if I want the inductance to increase in its value, I have to have a large number of turns. If I have a larger number of turns, I am going to get a good inductance value and reluctance has to be smaller that is what it is, so normally we use iron core inductors. But iron core inductors can result in very high hysteresis loss, especially if I am talking about high frequency of operation then any amount of hysteresis loss you get will be actually whatever is the area under the curve, BH loop multiplied by the frequency.

So if I work on higher and higher frequency, there will be extremely large hysteresis loss. So generally for high frequency inductors, we do not use iron core. We tend to use the right core or some kind of amorphous core. So there will be filings of iron, which will be filled inside, a probably a non-conducting material and then that will be used as the core. So those are generally known as powdered iron or kind of fillings of iron which will be actually not having any proper BH loop, because every iron acts like a separate entity there.

So that is the reason why you may not have a large amount of hysteresis loss. So normally we use something like this and there will be definitely more amount of air gap. You should understand that when I use iron fillings there will be definitely more amount of air gap so you would normally see that the leakage could be somewhat larger. So high frequency inductors will normally have larger amount of leakage and you will normally see that they are not made up of solid iron material because to avert the hysteresis losses that is the reason.

So if I am talking about the large power capacity boost converter first of all the number of turns have to be larger I told you, which means, I have to have thick conductors also high power means it will carry larger current, thick conductors making multiple number of turns around and amorphous core is not easy because it may not have the mechanical strength.

So generally boost converters especially in high power capacity have a limitation of about stepping up of 2 to 2.5 times generally not more than that, very rarely we see much higher capacity of boosting up of the voltage generally. So it has a limitation because of the inductance itself. So, inductance is generally a big headache in any of the converters normally and in boost converter it becomes a must, because buck converter if I am using it with a motor in all probability I may not even include an inductance explicitly, the motor inductance itself is sufficient enough, normal. So I may not even include any explicit inductance.

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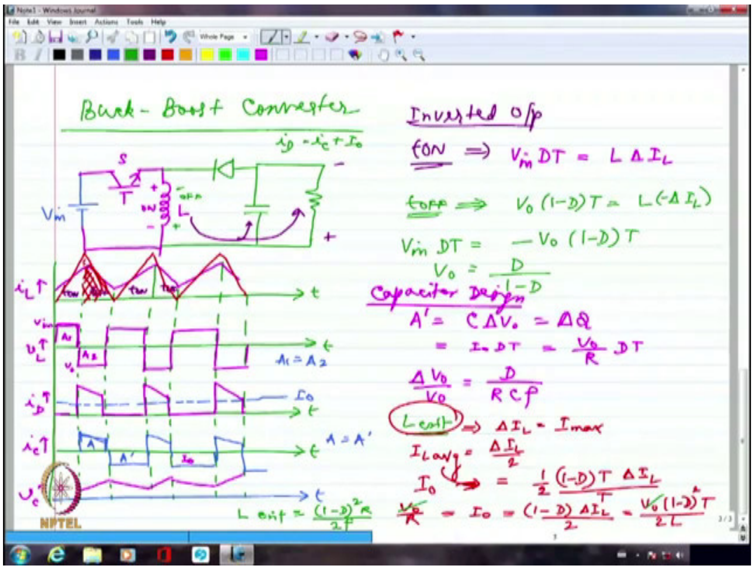

Inverted o/p

$t_{ON} \Rightarrow V_{in} DT = L \Delta I_L$

$t_{OFF} \Rightarrow V_o (1-D) T = L(-\Delta I_L)$

$V_{in} DT = -V_o (1-D) T$

$V_o = \frac{D}{1-D}$

Capacitor Design

$A' = C \Delta V_o = \Delta Q$

$= I_o DT = \frac{V_o}{R} DT$

$\frac{\Delta V_o}{V_o} = \frac{D}{RCf}$

$L_{crit} \Rightarrow \Delta I_L = I_{max}$

$I_{Lavg} = \frac{\Delta I_L}{2}$

$I_o = \frac{1}{2} \frac{(1-D) T \Delta I_L}{T}$

$\frac{V_o}{R} = I_o = \frac{(1-D) \Delta I_L}{2} = \frac{V_o (1-D)^2 T}{2L}$

So let us try to now go to the third type of converter which is actually a buck boost converter.

Student: How are you deriving average output current Io from average inductor current $I_{L(avg)}$?

Professor: We said basically that the inductance is always in the input side, so the inductance average value happens to be my input current average value as well. So $I_{L\ average} = I_{in\ average}$. So if I have that then with this lossless converter relationship I should be able to arrive at relationship between I_o, I_{in} and $I_{L\ average}$ that is what we have done. So, buck boost converter again have the same 3 components, 4 components that we talked about, a switch, an inductor, a capacitor, a diode, all these things.

So, let us say this is my input voltage V_{in} now we are going to have a switch here such that this is turned on and turned OFF, so this is my switch. Now I am going to have an inductance connected here, and this switch when it is turned on clearly it is short circuiting the inductance very similar to the boost action. Absolutely there is no difference whereas I am going to have a diode connected in this direction, please note it is in the opposite direction, and then I am going to have a capacitor here and a resistance here which is the load.

When the switch is on, I will have plus here and minus here this is during when switch is on. So it is storing the energy. When the switch is turned OFF inductance has to give back its energy. So, when it is giving back its energy, this is going to be minus and this is going to be plus, during the

OFF interval of the switch. So if it is like this, clearly, the inductance is going to release the current was flowing in the same direction, so the current would flow like this and like this, this is how the current is going to flow.

So please note that in this particular case I am going to have plus here and minus here as far as the output voltage is concerned, I will always have plus here and minus here. So it is actually inverted output. What I get as the output is in inverted polarity. So this particular converter generally is known as an inverted output converter because the output voltage is going to be in reverse polarity and in this particular case, I am going to have essentially the input and output are hardly ever connected.

Initially, when I am going to have the switch on the diode is not going to be on, so the diode is the isolation that is existing between the input and output and when I am turning OFF the switch, the switch is the isolation existing between the input and output. So it is completely isolated, the output is isolated from the input, they are not going to be connected together at all at any point in time. So if I try to write the relationship during t_{ON}, I am going to have it is very similar to the boost converter, there is hardly any difference between the boost converter equation and the buck converter equation as far as t_{ON} is concerned.

So, I am going to have, $V_{in}DT = L\Delta I_L$

Whereas, if I try to look at it during t_{OFF} the inductance voltage is actually equal to the output voltage. So, I am going to have actually $V_0(1-D)T = L(-\Delta I_L)$

if I have to take care of the sign I have to write, ΔI_L is now in the negative direction that is how you get V_o to be negative, because of ΔI_L being in the negative direction because it is actually decreasing, I am going to get essentially the inductance voltage is reversed because of which I am going to have the output voltage also reversed.

So, I would be able to write that $V_{in}DT = -V_0(1-D)T$

$$V_0 = \frac{D}{1-D}$$

The negative sign essentially indicates that the voltage is in the opposite polarity, the output voltage is in the opposite polarity as compared to the input voltage. So you do not even have to put the negative sign as long as you understand that the voltage is in the reverse polarity.

So, let us try to now look at the waveforms for this converter again. So if I try to draw the waveforms for this converter, so let us say this is the reference axis I am using and this is t, so I am going to have may be the inductance current is increasing like this and it is decreasing like this, and again, it is increasing like this, decreasing like this, somewhat like this. So this is the inductance current waveform I_L.

So let me try to draw the time axis. So, I am essentially looking at this as the inductance current. The inductance voltage is such that I am going to have V_{in} coming up as the inductance voltage which is corresponding to on time. So, this is V_{in}.

And during OFF time, I am going to get Vo, so if I am talking about the inductance stored energy -- net inductance stored energy is 0, I will have to have these two areas if I say A_1 and A_2 they have to be equal to each other. So this is actually V_L, what we have drawn here is V_L. So, we are going to have essentially this as V_{in} and this as V_o. So these two areas have to be equal to each other.

Now let us try to look at what is the kind of diode current that we are going to have. Diode conducts only during the input, I mean, only when the input switch is OFF, otherwise it is not going to conduct. So let us try to draw the diode current, the diode current is only corresponding to the OFF interval, so I am talking about this as t_{ON} and this as t_{OFF} again, this is t_{ON}, this is t_{OFF}. So, I have to draw it corresponding to the OFF interval, so I have to have something like this. Again, I have to have something like this, this is the diode current, and diode current if I try to look at the average value that will be my I_0

So, I have to draw I_0 somewhat like this, this is probably my I_0 value. Please note again, this is average over a complete period T. So, it will be less than even this value, it has to be less than that also, because it is average over the entire period. So, this is going to be Io from which I should be able to draw the capacitance current, capacitance current is whatever is the diode current minus this Io value. So, I have to write $i_D = i_C + I_0$, this is true in this particular case also.

So I have to write this as during wherever the diode current is 0, I am going to have Io and when the diode current is there I am probably going to have something like this, and again, I will have something like this and then I_0, this is how it is going to be. And if I again look at these areas, this is A and this is A', these two areas have to be equal to each other because the capacitors cannot retain any energy as such. So, these two areas have to be equal, so here A_1 equal to A_2 and here it is A equal to A'. So if I look at the capacitance voltage.

Student: How can you say that diode average current is average output current?

Professor: Why is the diode current?

Student: Average diode.

Professor: Diode current average is I_o, I should rather say that the output current average is I_o, but diode current if I try to look at over a cycle, the capacitance is discharging the energy for some time, but it is again accumulating the energy form diode only ultimately. So although it looks as though capacitance is providing the energy to the load, then the diode is not conducting ultimately even that energy is coming out of diode and inductance. So, I have to essentially average the diode current over the entire period I will be able to get I_0.

Otherwise I will not be getting I_0, because the capacitance whatever it is accumulating even for that short duration that is from the diode and that is what it is giving back to the load. So ultimately the diode current is giving the energy to the capacitance which it is providing to the load during the OFF interval. So if I look at the diode current over the complete period, then that will give me the output currents average because of that, because the diode is the one which is even providing for the capacitance, think about it, because capacitance where will it get the energy from?

It will get it from the inductance, but the inductance is essentially passing it through the diode, but I cannot say the inductance average current is same as I_0, no in fact inductance average current is neither I_0 nor I_{in}, because during initial condition it is ON interval it is I_{in} inductance current is I_{in} and OFF interval it is I_0. So, you cannot really say that it is exactly same as I_0 average or I_{in} average, we will have to calculate that also for getting L minimum.

So if I am looking at how really the capacitance voltage is increasing and decreasing, whenever I am getting a current from the diode which is charging the capacitor I am going to probably have increase in the capacitance voltage whenever it is discharging to the load it is going to decrease and so on and so forth. This is how it will be. So, this will be V_c whereas this will be I_c. It is quite easy to calculate the capacitance value, it is same as what you had in the other case that is the boost converter, we said basically I_0 is coming up so I can write,

$$A' = C\Delta V_0 = \Delta Q$$

$$= I_0 DT = \frac{V_0}{R} DT$$

$$\frac{\Delta V_0}{V_0} = \frac{D}{RCf}$$

which is same as that of the boost converter, because it looks almost similar, there is hardly any difference between the two.

Now we will have to look at the inductance value that is critical inductance value, so L critical. Then we are looking at L critical may be we will have a higher variation in the current, so it will go something like this and then come down, it will go something like this and come down and so on, this is how it is going to be. So I am going to have higher variation in the inductance current. So in this particular case of course I am going to have, $\Delta I_L = \mathrm{I}_{max}$ because it is touching 0, so whatever is the maximum amount of current that is going to be same as ΔI_L, because $\mathrm{I}_{\max}$ - $\mathrm{I}_{\min}$, $\mathrm{I}_{\min}$ is 0.

So if I try to look at what is the average inductor current? Let us try to get what is the average inductor current, I should say $I_{Lavg} = \frac{\Delta I_L}{2} = \frac{I_{\max}}{2}$. But how do I really equate this ultimately to I_0 or I_{in}? I have to look at that basically. So if I want actually I_{0avg} to be calculated in terms of whatever is the value that I am getting for, the inductance current, if I want to interpret what is my I_0 in terms of inductor current.

So, I need to essentially look at the current only during this duration, during the OFF duration because until ON duration the capacitance was giving out the current, but ultimately even that is because of the inductance stored energy, so we are coming back with a nice question again. So, whatever is your inductance current during the OFF interval, if I try to average it over the complete cycle that will actually come out to be my I_0,

$$I_0 = \frac{1}{2}\frac{(1-D)T\Delta I_L}{T}$$

Similarly if I try to look at the complete area under that right angle triangle during ON interval and then average it over the period that will give me I_{in} because I_{in} is actually same as whatever is the inductor current that is flowing only during the ON interval.

During OFF interval, I am not having any I_{in}, but I had to average it over the entire period if I want I_{inavg}. Same case, same is the case with respect to the inductor current, because inductor current is the one which is providing the complete energy to the capacitor as well if there is no other energy source, all the energy even inductance is accumulating is from V_{in}, so there is no other energy source. So, if I call this as Io, we are now trying to correlate whatever is the ripple that we are getting with that of I_0,

$$\frac{V_0}{R} = I_0 = \frac{(1-D)\Delta I_L}{2} = \frac{V_0(1-D)^2 T}{2L}$$

$$L_{crit} = \frac{(1-D)^2 R}{2F}$$

So this is L critical value. See this particular converter because the input and output are completely isolated, the average I_{in} and average I_0 calculation becomes a little tricky as compared to what you get in the other converters.

Other converters at least you get I_{in} as the inductor average current or I_0 as the average inductor current, but that does not happen in this case. So buck boost converter specifically find applications wherever we look at a huge range of variation of voltage in the DC supply which has to be converted finally into a particular constant value at the output for whatever reason, may be even for battery charging application.

Battery charging generally is done with the help of a rectifier most of the times, but there are applications where it may be done from solar PV. So the output voltage because it may vary, in a large range because of the temperature, you might require a buck boost converter in those cases to bring it back to whatever is the value that is acceptable by the battery ultimately. So these are very commonly used in solar PV applications.

So, so far whatever we have seen in all the cases we have assumed continuous conduction, at least critical conduction, we have never assumed that the inductor current can dwell at 0 value for longer, so let us try to take one case that is a buck converter case first where we will look at discontinuous conduction.

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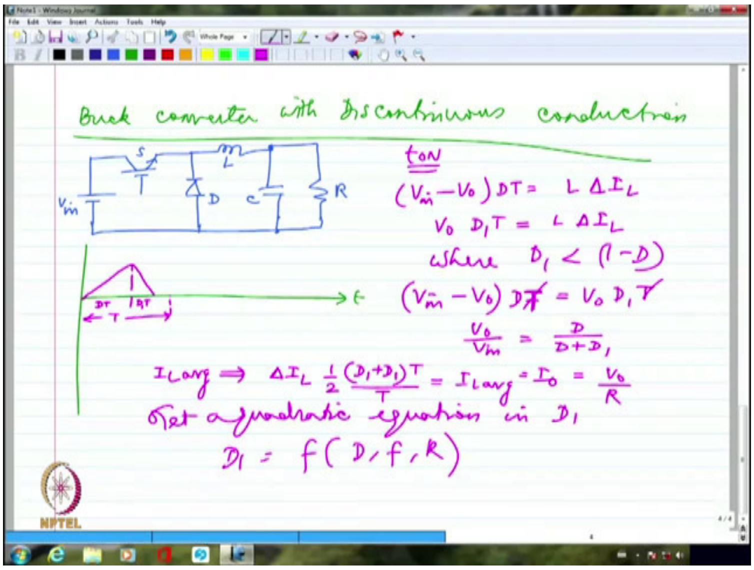

Buck converter with Discontinuous conduction

t_{ON}

$(V_{in} - V_0)DT = L\Delta I_L$

$V_0 D_1 T = L\Delta I_L$

where $D_1 < (1-D)$

$(V_{in} - V_0)D\cancel{T} = V_0 D_1 \cancel{T}$

$\frac{V_0}{V_{in}} = \frac{D}{D+D_1}$

$I_{Lavg} \Rightarrow \Delta I_L \frac{1}{2}\frac{(D_1+D_1)T}{T} = I_{Lavg} = I_0 = \frac{V_0}{R}$

Get a quadratic equation in D_1

$D_1 = f(D, f, R)$

So buck converter with discontinuous conduction, so when we have discontinuous conduction, the equations becomes somewhat complex, they are not really as simple as what it had been so far. So, we are looking at the buck converter, again, I am going to have essentially a switch here which is in series and then I am going to have a diode, then I am going to have an inductance, a capacitance and the load. So, we said that when the switch is ON we are going to have inductance accumulating energy.

May be we have not kept the switch ON for long enough so that the inductance energy could be accumulated, so that it can drive the current for the entire OFF duration or may be the input voltage is not large enough that is also a possibility or the inductance is not large enough, anyone of them, whatever is the case. May be I am going to have otherwise the resistance to be very large, the resistance is large then also the current will be small. So, if the load is large or the input supply voltage is small or the input inductance value is not large enough or I have not kept it ON for quite a long time duty ratio is not large enough, the inductance stored energy will become pretty small in that case.

So if I actually look at the inductance waveform, current waveform I expect that generally the current should start from a non-zero value, but it may not start from a non-zero value, because the inductance is not having sufficient stored energy, so I may have the inductance current rising like this and it may fall down quickly. And still there is time for the switch to be fired again. So, which means, I am not going to have this to be completely equal to t_{OFF}, rather my T probably is going to be longer than this.

So what I am having is this is DT, this is D_1T, which is not $1-D$, $D_1 < (1-D)$, so I am not going to really have the inductance continue to conduct for the entire OFF duration because the energy is not sufficient enough only this much is going to be my D_1T. So under this condition, I have to write during ON interval,

$$(V_{in} - V_0)DT = L\Delta I_L$$

So previously we wrote this as $V_0(1-D)T$,now I cannot write that because it is not conducting for the entire duration, so I have to write this as $V_0D_1T = L\Delta I_L$

where I am going to have $D_1 < (1-D)$. So now I have to equate these two. So I should say,

$$(V_{in} - V_0)DT = V_0D_1T$$

$$\frac{V_0}{V_{in}} = \frac{D}{D+D_1}$$

When it was continuous conduction, $D_1 = 1 - D$, that is why we could get $\frac{D}{1}$,So it was simply $DV_{in} = V_0$. So you have to actually look at how to solve for this D1, we be able to solve for D1. So if I am actually looking at what is the inductance average current in this particular case? That will be same as I_0. So, get what is I_{Lavg} and then that can be solved for by actually solving this, this is essentially what is the area under this curve,

$$I_{Lavg} = \Delta I_L \frac{1}{2} \frac{(D_1 + D_1)T}{T} = I_{Lavg} = I_0 = \frac{V_0}{R}$$

So I can write V_0 in terms of D by D + D1 and so on and so forth, but I should be able to get a quadratic equation in D1 ultimately which I can solve for, I want you guys to do that, get this again equated in terms and D and D1, and then you will be able to get ultimately a quadratic equation in terms of D1.

So get a quadratic equation in terms of D1, D I already know, D1 is the one which I have to solve for, so $D_1 = f(D, f, R)$ and so on, these things will be there in the equation, you would be able to arrive at what is the D1 value. So that gives you a complete close form expression for the input-output relationship.

So when you solve a problem in the buck converter for example, if you find that the inductance current ultimately is going to negative for a given value of inductance, for a given value of duty ratio, for a given value of V_{in}, V_0 and R, if you are getting the inductance current to be going in the negative direction, then that it is actually getting into discontinuous conduction, because inductance current cannot go in the negative direction in the DC-DC converter.

The moment you get a negative current, then it is going into actually a discontinuous conduction mode, so at that point you should be able to actually solve for D1 by using whatever you are going to derive as the quadratic equation from that you will be able to derive the expression for D1 which you will be able to solve for. Once you get that, then the rest of the things will be, directly possible for you to arrive at all the relationships, not a problem at all.

So whenever you actually are given a problem, first of all, you have to make sure that it is in continuous conduction mode. If it is not in continuous conduction mode, you cannot use the expression whatever we derived earlier. One way of doing it is may be you can check what is L critical value, you have that expression and if the inductance given is actually smaller than L critical, it has already been in discontinuous conduction mode for the given operation and then you can calculate what is D_1 and so on and so forth.

So you can do it either way, either you first of solve for inductance current or you solve for what is the inductance value and then you try to see whether it is above critical conduction mode or below critical conduction mode. We have one more converter in non-isolated category again which is known as Cuk converter , generally many people call it as Cuk converter. So Cuk converter is extensively used in many applications because of which, I would definitely like to take that up as well.

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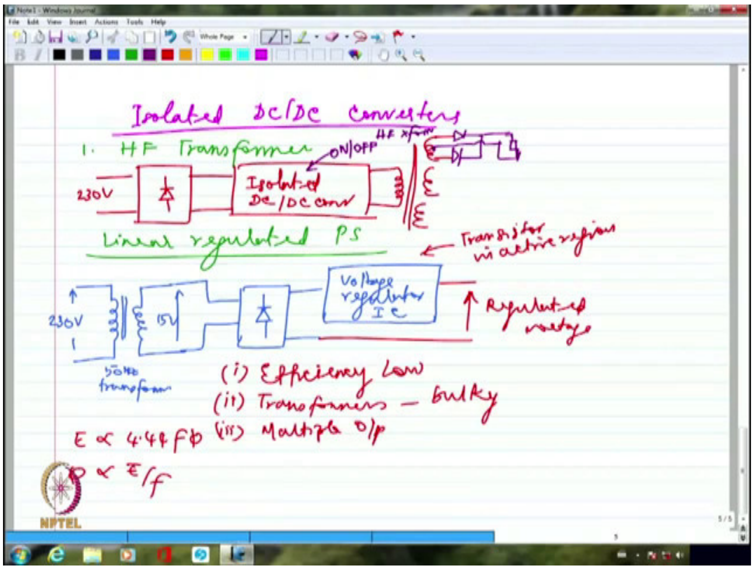

So in isolated DC-DC converters the major difference is that I am going to have a transformer, invariably I will have a high frequency transformer which will be isolating between the input side and output side. There will be a high frequency transformer which will be used for isolating the input side from the output side, which is needed in many of the cases, because for example, if you look at your computers where we are using SMPS, in those cases, what we give it to the ICs they are all 5 volts, 3.3 volts, 12 volts and so on.

Whereas what we give from the UPS is 230 volts, so the power ground and the ground of electronics we would not like to connect them together, unless we have a transformer in between them, we will not be able to provide isolation between the ground of the power side and ground of the electronic side. So that is one reason why most of the switch mode power supply will use the transformer. You can very well use 50 hertz transformer as well.

Normally what you have is regulated power supply in your laboratory what is done normally is, so in linear regulated power supply versus SMPS, I would like to show the difference. In the linear regulated power supply, normally most of the times what is done is, I am going to use a 50 hertz transformer right up front. So an isolation is provided there also, in most of the linear regulated power supply, I will have isolation, but it will be a 50 hertz transformer normally.

So what I have is 230 volts I will step it down to 5 volts or 15 volts or something of that sort depending upon what is the kind of output I require, if it is a regulated power supply with 12 volts, I may have 230 by 15 volts transformer. Now whatever is the output of this transformer, so this is a 50 hertz transformer. Now the output of this transformer is going to be rectified in all probability with the help of a simple diode bridge rectifier, this diode bridge rectifiers output will be given to a voltage regulator.

The voltage regulator is generally a transistor working in active region, so if it is working in active region, V_{CE} is not minimum, V_{CE} value is going to be fairly large depending upon how much is the base drive that we are using. So it is not like IGBT or MOSFET that we use in power electronic where it will be completely into saturation or completely in cut OFF region whereas here it is going to be in active region, so we will have a transistor, so this is generally a voltage regulator IC which will be used. This will be basically a transistor in active region.

So which means it is going to drop a huge amount of voltage, so 15 volts when I probably use a full wave rectifier I will get about 14 volts or something. So 2 volts, 3 volts something will be dropped, if I want 10 volts, almost 4 volts are going to be dropped. So it is also carrying full current, so you can imagine the copper losses that take place within this small transistor, a huge amount of copper losses will take place because of which I had to put a large heat sink. The heat sink that I am going to put for this regulator IC, if you ever put your hands on that regulator IC you will get a burn normally.

It will be really-really hot because of a huge amount of copper losses that is taking place. Now whatever is the output now this will be regulated voltage. Inside the voltage regulator IC there will be mainly two components, one will be a transistor in active region another will be a zener diode. The zener diode will normally maintain what is the reference voltage I require and there will be some kind of comparison between that zener diode voltage and the actual output voltage and then that whatever is the difference that will go at the drive, that will set the drive value based drive value for the transistor.

So, it will be driven, as per whatever is the error voltage that is available. So the more the error, the more probably I will have to drop as the voltage and then, the more will be the copper loss so on and so forth. So the voltage regulator is supposed to maintain the output voltage as a constant irrespective of any supply voltage variation because understand that this is not 230 volts always, although, we say it is 230 volts. It may be 180 at some point, it can be 260 at some point, so what I get as the voltage here is unregulated.

So we regulate this with the help of this voltage regulator IC, so the major problem that linear regulated power supply is 2 volt or I would say 3, one is I am not going to be able to, reduce the copper losses, which means efficiency is generally low, I will not have a good efficiency, this is one problem. The second problem that I normally would face with this is because of the 50 hertz transformer here, it is going to be bulky.

The transformer equation is $E \propto 4.44 f \Phi$ and number of turns. This is what we derived as the transformer voltage equation. So, I can say $\Phi \propto \frac{E}{f}$ or $\frac{V}{f}$, E is approximately equal to V. So if I am talking about a 230 volts, 50 hertz transformer if the flux happens to be let us say 2 weber for example, when I talk about the same 230 volts, but may be 50 kilo hertz transformer, the flux will be 2×10^{-3} weber.

The flux will decrease tremendously when I talked about larger frequency transformers. So if I talk about the particular material which can have a flux density of 1.2 weber per meter square, if I use the same material for a 50 kilo hertz transformer I can really make very-very small cross sectional area for my core of the transformer. So obviously because the flux requirement decrease with increase in frequency, the transformers would get miniaturized, they will become really-really tiny when I go for larger and larger frequencies.

That is one reason why I think, I mentioned is definitely in electro-mechanics class, aerospace electronic systems or aerospace machines generally whatever is used in aircrafts they all operate at 400 hertz, they never operate at 50 hertz. So it is like a trade-off, you do not want too much of inductive reactance to come into picture in the machine as the drop, leakage reactance like you do not want too much, but you do not want very bulky machines also, so it is like a trade-off, they have arrive it at 400 hertz as a standard for aerospace machines, generally aircraft machines in the aircraft.

So, when we talk about linear regulated power supply, the transformers become bulky because they are operating at 50 hertz, so if we try to operate it at a higher frequency like using a DC-DC converter and use a high frequency transformer, like what we do in the case of SMPS, that is why SMPS is really tiny. If you look at many of the computer power supply, they will be really tiny because of high frequency link coming into picture somewhere.

The third disadvantage of linear regulated power supply is generally for every output, I may use independently 3 regulator ICs and so on and so forth, whereas when I use the high frequency transformer towards the output, if I try to use it towards the output side, the primary wave may have a particular voltage, I can have multiple secondaries, one can feed 5 volts, one can feed 12 volts, another one can feed minus 12 volts, the fourth one can feed 3.3 volts and so on.

So SMPS generally will have single primary and multiple secondary in the high frequency transformers that are used at the end. Because of which I would be able to get multiple outputs from a single input feeding line whereas that does not happen most of the times in linear regulated power supplies.

So here I would be able to obtain multiple outputs stiffly regulated, I can regulate them very stiffly, that is not a problem, because the DC-DC converter what I use actually in this particular case, I will be able to turn in turn ON and turn OFF from saturation region I can go to cut off and back because of which there will not be much of copper losses so efficiency is good, and I would be able to use high frequency transformer, so it will be tiny and it will save on space and the third one what I have is basically multiple output I will be able to obtain by having multiple secondaries.

So we would be looking at so SMPS if I try to show basic diagram, it will have basically 230 volts from which I may have a diode converter and what I have here, I have the output will be of the order of maybe 230, 220 volts, if I do not put a capacitor, if I put a high value capacitor, then it will charge up to the peak. If I do not put a capacitor, this output will be given to a isolated DC to DC converter. So at the output of the isolated DC-DC converter, normally we will have a transformer. So I may have single primary at the output of the isolated DC-DC converter with multiple secondaries.

So this will give output 1, of course, if I am talking about a high frequency transformer, what I get as the output here maybe AC, if I have to convert that into DC that rectifier is also part of isolated DC-DC converter, I am showing it explicitly, because I wanted to show the high frequency transformer. So this is the high frequency transformer and the output normally will have a center-tap rectifier, something like this.

So I am going to have 2 diodes and the load is connected between these two terminals, this is a center-tap rectifier, what we initially started with. Normally we will use a center-tap rectifier in the power supply so that only one diode will conduct at a time, the drop will be smaller. Of course, there are multiple stages, but we are going to operate this converter only in either on or OFF, so on-OFF control we will be using, so we will not have much of losses in this particular converter. So this is way normally a SMPS is constructed. So we will go into isolated DC-DC converter in the next class. Thank you.