Power Electronics
Professor G. Bhuvaneswari
Department of Electrical Engineering
Indian Institute of Technology Delhi
Lecture 18 - Isolated DC-DC Converters-II and CUK Converter

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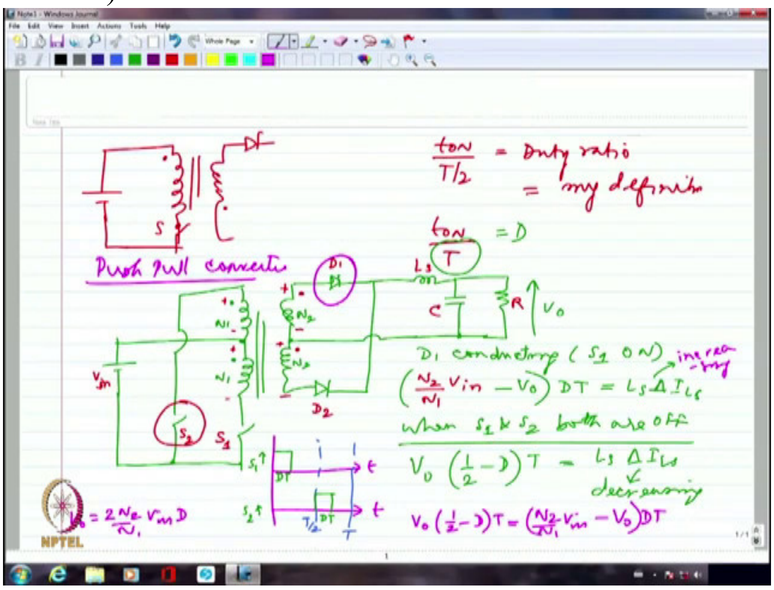

So, let us go over with the isolated DC-DC converters. We had come until push pull. In push pull, the way the duty ratio is defined in Daniel Hart is a little different from what I had defined. I had defined basically whatever is the on-time divided by $\frac{T}{2}$ as the duty ratio. This is what I had defined. This was my definition whereas Daniel Hart, actually he is defining this as $\frac{t_{ON}}{T}$, the entire T and t_{ON} of every switch. There are 2 switches.

So if you actually look at the push pull configuration, I am going to have essentially 2 transformer windings like this and one is connected through a switch here, this is connected in the middle and the other one is connected through the second switch. This is how they are connected. And we said that if we are defining the dot here, this has to be the dot because I am assuming that they are connected in series, not in anti-series. They will add up together in terms of voltage.

On the other side I am going to have again 2 secondary windings. So if I may call this as N_1, this is also N_1 whereas this is N_2, this is also N_2, the number of turns are N_2. So I am going to have here a diode, one more diode here, center-tapped rectifier configuration and then I am going to have from here an inductance. A freewheeling diode is not necessary because these 2 diodes will be able to take the function of the freewheeling diode. I do not have to put any explicit freewheeling diode and after which I am going to have a capacitor and a resistance.

So this is the load and this is my L_s. That is what we took as the inductance which is similar to the inductance in a buck converter. That is what we took. Now if I am turning this on, I am going to get a positive here and negative here that is when S, let us say this is some S_1 and this is S_2. These are the 2 switches. When S_1 is on, I am going to have positive here and negative here. So correspondingly I will have positive here and negative here. That is why we said that whatever is the voltage across the switch will be twice whatever is the voltage across one half of the primary.

So, at this point if I want one of the diodes to conduct, let us say this is D_1 and this is D 2. If when N_1 is on, if I want D_1 to conduct I should have probably the dot along this , hopefully; so if I have the dot along this and I have the other dot along this so I will have positive here, negative here again positive here, negative here. So D_2 will be reverse biased and D_1 will be forward biased, So D_1 is forward biased and whatever is the voltage that is coming across this secondary will be $\frac{N_2}{N_1}V_{in}$.So I will have D_1 conducting during when I am going to have S_1 on. This is going to be the voltage and I have V_o here and that V_o is fairly a constant because the capacitance value is fairly large, the ripple is minimum. So, we can say,

$$\left(\frac{N_2}{N_1}V_{in} - V_0\right)DT = L_s \Delta I_s$$

This is during the on interval. And when I turn it off it is exactly similar to what we had in the case of the buck converter when we had turned off the switch.

So when both of them are not conducting that is off interval, when S_1 and S_2 both are off. Under this condition what he has written is $V_0\left(\frac{1}{2} - D\right)T$. S_1 is on for a very short while in

$\frac{T}{2}$ then we are going to turn both of them off, then $\frac{T}{2}$ you have reached. Then the entire circuit has reached the point of $\frac{T}{2}$ time. Then you are going to turn on S_2.

Then $\frac{T}{2}$ plus whatever is the time duration of t_{ON}, for that duration second switch is going to be on. So we are essentially looking at something like this, the waveform will be somewhat like this. If this is my t, I am going to have, for initially this is let us say $\frac{T}{2}$ and this is T. So I am going to have one of the switch is on for some time. Then the next switch is going to be on for some time. So this duration we are calling as DT, this duration also we are calling as DT. This is on corresponding to S 1 and this is the pulse corresponding to S_2.

[Professor – student conversation starts]

Student: $1-D$

Professor: $(1-D)\frac{T}{2}$ we should have done provided we assume that whatever I had done, $\frac{t_{ON}}{\frac{T}{2}}$ is the duty ratio if I assume then that is. But as per Daniel Hart, he has essentially assumed $\frac{t_{ON}}{T}=D$, so he is not taking $\frac{T}{2}$ here, he is taking T. That is the reason why we are looking at this little differently.

[Professor – student conversation ends]

There is nothing wrong if you get a 2 factor or you do not get a 2 factor as long as you define your duty ratio properly, as simple as that, As long as you define your duty ratio properly, what is duty ratio, then it is perfectly fine. So this is essentially the off interval. So I am going to get ,$V_0\left(\frac{1}{2}-D\right)T=L_s\Delta I_{Ls}$ in steady state where this is decreasing current whereas this is increasing current.

Now you have to just equate these two from which you should be able to get whatever is your expression for V_{in}/V_o .So we can say,

$$V_0\left(\frac{1}{2}-D\right)T=\left(\frac{N_2}{N_1}V_{in}-V_0\right)DT$$

so this will be essentially when you add the two you should be able to get finally whatever is your, this 2 factor will also come into picture. $V_0=2\frac{N_2}{N_1}V_{in}D$

That is what we will get as the overall expression for your output voltage, because of the way we have defined the duty ratio. So the same thing holds good very clearly for S_1 and one more thing you have to remember is this particular switch is also going to face twice the voltage as the reverse biasing voltage, whatever is the output voltage if I may say that is $V_{in}\frac{N_1}{N_2}$, each of the diodes will also face twice that voltage.

$\frac{N_2}{N_1}V_{in}$, if that is the voltage that is coming up as the output, that multiplied by 2 will be faced by each of the diode which is not conducting at that instant because the secondary voltage is induced on the other side also. It will not conduct, but the voltage is very much induced. It is open circuit voltage which will come up across any diode which is not conducting. So, the diodes have to be rated for much higher voltage. Same is the case with the devices. These also have to be rated for much higher voltage than whatever actually they are delivering. They are delivering much less.

So this kind of one diode conduction, this is what we talked about earlier. In power supplies what we worry about is the drop. So if the output is only 5 volts you do not want to have 1.4 volts as the drop. That is the reason why we do not use bridge rectifier. If we use the bridge rectifier, 2 diodes will come into picture in terms of the conduction path and you want to avoid it. That is the reason why we normally use this although the voltage rating becomes much higher, and if it is a 15 volts circuit you have to rate it for 30 volts and a factor of safety.

That is not much really because the voltage rating actually, unless you go beyond kilovolts the cost does not increase tremendously. Only when you go beyond kilovolts level the cost increases tremendously. The currents or the overall power rating increases the cost quite a bit and more than anything in power supply we are worried about regulating the output voltage.

So, we do not want to have too much of drop and too much of drop means there will be definitely lot of copper losses across the devices. That means you have to put bigger heat sinks and then the size will increase further and further. So, you do not want to increase the size quite a bit. so much so far, the push pull converter. The last 2 converters in isolated topology are half-bridge and full-bridge.

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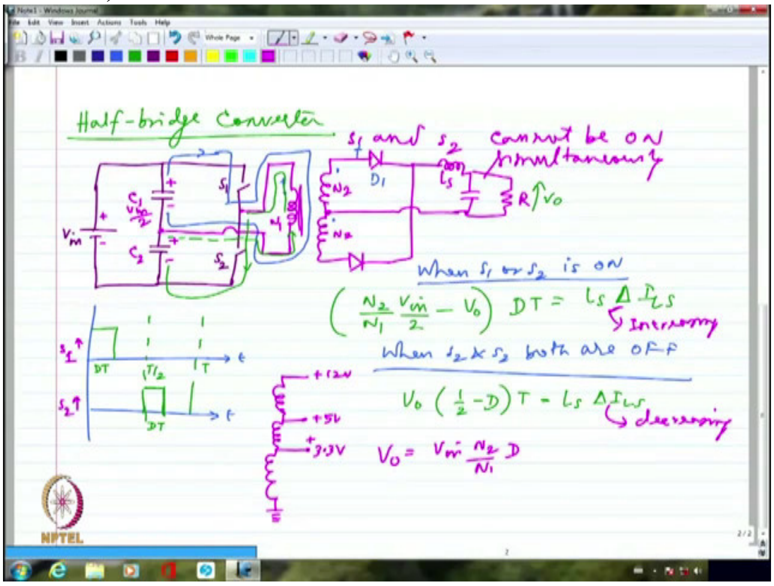

So, let us look at half-bridge converter. We will revisit this half-bridge topology again when we come to inverters. We will be looking at this extensively but right now let us look at this especially as one part of the DC-D C converter. So half-bridge is a general circuit which can be used for D C to A C conversion as well. So, this is my input voltage and I am going to have 2 capacitors connected which will divide the voltage equally because we will choose in such a way that the values are the same and they are connected in series which means half the voltage will come across each of them.

Now we will have one switch here and one more switch here. And let me call this as S_1 and this as S_2. They are complementary. We will not have S_1 and S_2 on simultaneously because if I try to turn on both of them simultaneously there will be a dead short circuit across the capacitor. That condition is generally known as shoot through. Shoot through is deadly for any of the inverter circuits or any kind of bridge circuit because you are going to essentially short circuit the entire capacitor path, the currents will be enormously high across the switches as well as across the capacitance. So, it is not good.

So, shoot through we have to avoid so S_1 and S_2 cannot be on simultaneously. So even if we assume that S_1 is going to conduct for 50 percent of the duration and S_2 is going to conduct for 50 percent of the duration we have to necessarily give a small delay between S_1 and S_2 which we call as dead band. Normally we call that as a dead band; in the inverter very often, we may have a complete square wave output. S_1 when it conducts, maybe we will get a positive voltage; when S_2 gets conduct, it will be a negative voltage but between S_1 and S_2 we necessarily need to give a small delay.

S_1 has to turn off completely before S_2 takes over like what we talked about in the case of cycloconverter, same thing. So, we have to make sure that P converter is turned off before N converter gets the firing signal. It is the same thing. So here S_1 and S_2 have to be completely mutually exclusive. Now from here I am going to take the output to the primary of a transformer like this. So, if I say this is plus, this is minus, very clearly this is plus, this is minus. This is plus, this is minus. This is how it is going to be and let me call this as C_1, this as C_2.

If I turn S_1 on I am going to have, let me say this has N_1 turns, it is essentially going to, the current is going to flow through the capacitor through S_1 into this winding and then it is going to return to the same capacitor. This is how it is going to be. This is the path as far as the current is concerned.

Please note, under this condition capacitance 1 is discharging, capacitor 2 is idling. So sometimes what we face as the problem is that C_1 gets discharged quite a bit even within a few microseconds or a few milliseconds and C_2 actually gets overcharged because the voltage is V_{in} across C_1 and C_2 put together.

So sometimes we face the problem of a voltage imbalance between C_1 and C_2. But if we choose sufficiently a large switching frequency, then we would not be seeing this much because the time constant involved will be quite large, because capacitance values are normally large because of which the imbalance will not be visualized so much, normally, but this is normally a prevalent problem especially in inverter, when I use this as an inverter circuit. So when S_1 is on I am going to get again, let us say this is S_1 signal and this is probably $\frac{T}{2}$, and this is going to be T, so this is corresponding to S_1's firing signal.

So if I try to draw what is the firing signal for S_2, I am going to again have S_2 conducting from here for the same DT duration. So if I call this as DT this will also be DT. So this particular signal corresponds to the firing pulse of S_2. Now what is available on this side will be whatever is the voltage that is coming up, that is $\frac{V_{in}}{2}$.

So what I get as the voltage whenever any of the switches will be on will be $\frac{V_{in}}{2}$, neglecting the imbalance between the two capacitor voltages because this is going to be my load. I am going to show the load on this side. I have the secondary here like this. So, let us say, this is N_2, this is also N_2. And I am going to have diode, here also a diode, same thing as what we got as the center-tapped rectifier, so I am going to have the load here which means again an inductance, capacitance and a resistance.

So, this is my L_s. And this is R, same as what we got earlier. So, if I say that for example the dot for this is here, I can show the dot here, then dot here. So, if I say that S_1 is on, I am getting positive here during this portion. So obviously this will be positive. So, this will conduct. D_1 will conduct. And when I turn off S_1 and turn on S_2, at that point I am again going to get the voltage in the opposite sense.

Look at the conduction path. So, I am going to have from plus, it is going to go like this in this direction, and then it is going to go like this and return through S_2. So, the current is flowing in the opposite sense in the winding. So you create positive half and negative half across this winding which is the high frequency transformer primary winding as and when you turn on S_1 and S_2 respectively.

So this is all square wave clearly. Whatever we are getting is a square wave because we are giving V_{in} which is a constant value. So DC-D C converter, there is no problem but when we are looking at inverter we have to look at modulating this wave in such a way that we get a sinusoid. How do we get a sinusoid, that is a major chunk of, the control of the inverter right which we will be looking at eventually.

So we are essentially looking at this as the voltage, so if I look at what is the voltage here, it will be,

$$\left(\frac{N_2}{N_1}\frac{V_{in}}{2} - V_0\right)DT = L_s \Delta I_{Ls}$$

This is when S_1 or S_2 is on; anyone of them is on, along with that of course either D_1 or D_2 will be on.

So similarly, in off condition, and S_2 both are off, we are going to get,

$$V_0\left(\frac{1}{2} - D\right)T = L_s \Delta I_{Ls}$$

I am using exactly the notion of Daniel Hart. so here this is increasing current.

This current is increasing whereas this is decreasing. So, there will not be the 2 factor because this 2 factor will get cancelled with the 2 factor what we are getting here in the other one. So I think you will get something like,

$$V_0 = V_{in}\frac{N_2}{N_1}D.$$

This is what you should be getting as the output voltage in this particular case which is half-bridge. And when we use half-bridge, generally in many of the computer power supplies what we use is half-bridge. PC, personal computer, SMPS what we use is half-bridge.

Generally, we will have one single primary and either multiple secondaries or if we are talking about 3.3 volts then 5 volts and 12 volts, so we may have one single secondary with multiple number of turns with taps. So, I can get may be 3.3 volts from here plus 5 volts from here plus 12 volts from here. If I need plus 15 or something, I can have more number of turns but I can ground this portion. This can be grounded. This ground is different from the primary side ground. The primary side ground is connected to the high voltage power supply.

In all probability I may have 230 volts, I will have a diode rectifier, a capacitor filter which is giving me V_{in}, and after that I am stepping down everything using a high frequency transformer. So, this side ground whatever I have is different from the other side ground. That this side is power ground whereas this side is going to be electronics ground which is low voltage and low current compared to what I will have on this side. This will be high voltage, and if I want negative voltage then I might have to just make it the opposite way.

I will ground the positive terminal and the negative side will be actually available as the negative voltage, that is it. So, this is the way normally you are going to have the half-bridge converter working especially in PC power supplies. So, they want to utilize the core to the maximum extent just by using the same thing, so this might carry higher current because this has to supply whatever is 3.3 and 5 also, so this is common to both. So, it will carry really a large current. So, when we design the transformer winding we have to be really careful in terms of the rating what we are choosing for the current carrying capacity.

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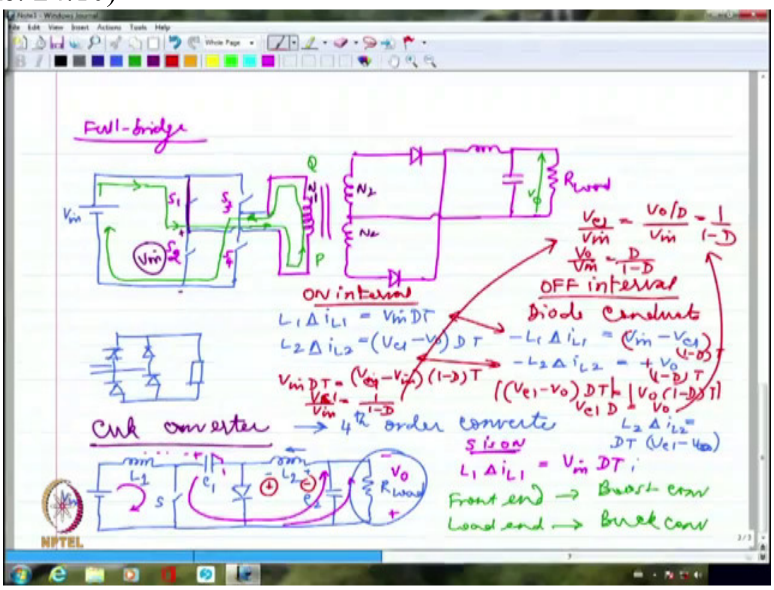

The last one in isolated DC-DC converter is full-bridge and full-bridge is used in many applications where we require very high power like 10 kilowatt, 15 kilowatt rating. So, it starts almost from 100, 200 watts. It extends until easily 15 kilowatts, 10-15 kilowatts, so it is having a very versatile range in terms of its application.

So, in full-bridge I am going to have this as my DC power supply which is V_{in} and the connection is very similar to what we saw as the full-bridge rectifier. So, I am going to have two switches connected in one leg of the bridge and there are 2 legs basically. So, if you may recall we used to draw this as the full-bridge converter. These are the 2 diodes, and these are the 2 diodes and we used to connect the DC here. It is exactly the same way. DC load is connected here, and AC is here.
Similarly, we are going to tap our AC from here. The AC is tapped from here and then we are going to have the primary of the transformer connected here. Let me call this as S_1, S_4 like what we had numbered earlier. This is S_2, S_3 Or S_3, S_2 either way is fine. So, we should say S_1 and S_2 are complimentary. S_3 and S_4 are complimentary. They will not conduct at the same time. They are mutually exclusive, because if I try to give firing pulses to both of them, again there will a shoot through.

So I have to be careful not to give the firing pulses to S_1 and S_2 together and S_3 and S_4 together. So if I am having S_1 and S_4 conducting I am going to have the current flowing like this, flowing from here, flowing through this like this and then it will come down through S_4 and return to the negative. This is the way it is going to conduct. This is the path that I am going to have.

So maybe this is P, this is Q so the current is going from P to Q whereas if I am going to switch off these two devices and then turn on the other two, I will from Q to P, the current will go from Q to P. So, I will have basically alternating voltages produced across the primary by switching action.

Now again on this side we will have 2 secondaries. Again, the same center-tapped rectifier, so I am going to have one diode here, one diode here and then these 2 and then I am going to have again an inductance and resistance. So, this is the load. So, I call this as V_o. So, you can again write the equation for this. It should not be such a major issue. If I just call this as number of turns as N_1, here N_2 and N_2, this N_1.

So you should be able to write the equations corresponding to the on interval of S_1 and S_4, and again on interval of S_2 and S_3 and then off interval of all of the switches. Only thing is here, each of the switches will be rated only for V_{in} or even less than that. Think about it. If I am going to have this on, then I am having essentially the positive terminal connected here and negative terminal is connected here.

So very clearly the voltage that comes across this will be V_{in}. It will be blocking V_{in} when I am having any of the switches on in the same leg; the other switch will be blocking V_{in}. So if we rate it for V_{in} that is good enough unlike what we have in the case of push-pull and so on. So that is the advantage of full-bridge. You do not have to choose devices of extremely large rating. The stress across the device is limited to whatever is the voltage that it is delivering, nothing more than that. So, I have not gotten into discontinuous conduction modes. Mostly I have only confined myself to continuous conduction mode.

But only one converter is pending now which is the CUK converter or however people pronounce it, so this converter is a very, very important converter which is having plenty of applications. So, I would not like to leave it out. That is the reason we are looking at this. This also we look mainly for continuous conduction mode. That is about it. So, with this we will conclude our discussion on DC-DC converter. So, this is the last converter that we are going to discuss. This is not an isolated converter.

Many of these converters also can be made isolated because wherever inductances are there, they can incorporate a transformer. It is not that they cannot. Wherever inductances are there you can think of a leakage reactance of the transformer working as an inductance. That is not a big deal. So many times, what is non-isolated, what is non-isolated converter can be made into an isolated converter by making the inductance represented by a transformer. So, you can make it isolated if it is required to do so

So, let us try to take a look at this converter. This is generally known as the fourth order converter whereas many of the other converters so far whatever we have discussed like buck or boost, or buck boost, they have only one inductance and one capacitor. So even if we write the differential equation, maximum it will be a second order differential equation, nothing more than that, normally.

So that is the reason why all those converters, the fundamental converters we discussed, buck, boost and buck boost, all of them are second order converters whereas this will have two inductances and two capacitances because of which we call this as a fourth order converter. And this is the pretty versatile converter. It is extensively used in telecom tower power supplies. It is used in some of the higher rated power supplies which may be used for different kinds of application.

For example your microwave oven, that will have definitely a power supply ,because it does not work on 230 volts, 230 volts is coming in but what we generate is the very high frequency wave, high frequency voltage ultimately which is going to create the microwave, ultimately which is heating up the material that you have put inside the microwave oven. So that has an SMPS sitting inside.

Many of our electronic appliances will have SMPS sitting inside which may be requiring higher wattage capacity. So, in those cases we will normally use probably one of the converters which can withstand much higher power rating. So CUK is one of those converters which can be used in even higher power ratings.

So, the CUK converter looks somewhat like this. This is my input voltage and I am going to have one inductance, let me call this as L_1 because there is one more coming up and then we are going to have actually a switch, maybe a MOSFET or IGBT, one of them sitting here.

So, this is the switch. So, the front end looks exactly like a boost converter. The boost converter starts like this, so front end looks exactly like a boost converter. After this I am going to have a capacitor and the capacitor values chosen are generally large because of which the ripples are generally neglected, whatever is the ripple across the capacitance voltages those are neglected. So, this will be a capacitance.

Unlike what we have seen so far in the non-isolated converters where the inductance was mainly transferring the energy from the input side to output side, here this capacitance will play a very, very vital role in transferring the energy. So, this capacitance is really going to act like a energy transfer device in this particular circuit. After this we have a diode and then we have another inductance which we call as L_2, and then we are going to have a capacitor C_2 and then we have the load here.

So, this is the resistive load that we are considering for this. So, let us try to take a look at the basic functioning of the converter. So, let us say S is on. When S is on, I am going to have this inductance storing the energy, clearly like what happens in a boost converter. So, one path is clearly, it is going to just circulate a current like this. So, I should be able to write,

$$L_1 \Delta i_{L1} = V_{in} DT$$

So, this is as far as the inductance 1 is concerned. Let us try to take a look at what happens to inductance 2.

See this is going to get charged initially even before I turn on the switch. When I connect everything together, actually a current can flow like this because the diode will conduct anyway initially. So the capacitance would have gotten charged anyway to a value which is slightly greater than V_{in} because the inductance stored energy will also be dumped into the capacitor, because this current will continue even after the capacitance has been charged to V_{in}

So, the inductance current will continue because of which its energy will be dumped into the capacitor C_1. So, when I switch on this particular switch because the capacitance is already pre-charged, it will be able to circulate the current somewhat like this. So, it will be able to circulate the current through L_2 as well as maybe the load. It will be able to do the circulation somewhat like this. So, the voltage across this, if I may call this as V_o please note that it will have plus here and minus here, it will be in the reverse polarity clearly.

So, this converter is somewhat similar to buck boost converter where we had a reverse polarity at the output, so something similar to that is happening in this case. If actually I forget about this portion and look at only the output side portion, it looks as though it is a buck converter, because you have an inductance, you have a capacitance, you have a load; all those things with the source as capacitance.

Whatever is V_{c1}, if I consider that as the source for my buck converter it is essentially looking like a buck converter because you can look at the diode also which is in the freewheeling direction correctly. It is not a big deal, so you can make out that, this is essentially like a buck converter.

So, the front end is like a boost converter and back end or I can say load end is like a buck converter. So, once you turn off this switch, then this is essentially a boosting action. So $V_{in} + L\frac{di}{dt}$, whatever was the energy stored here that will be dumped into the capacitor. So, the capacitor gets replenished during off interval. During on interval the capacitance is supplying actually to the load and indirectly it is also supplying an energy to the inductor. So L_2 will also be storing energy which it is deriving from capacitor C_1.

So, you are going to see that this current which is flowing through L_2 is actually charging the inductor. So, if you actually write the equation corresponding to L_2, I should write again

$$L_2 \Delta i_{L2} = \left(V_{c1} - V_0\right) DT$$

which is very similar to what we see normally in the buck converter.

So, I have simultaneously 2 equations being written, one for L_1, the other one for L_2, So let me write the equations here in a little bigger way.

$$L_1 \Delta i_{L1} = V_{in} DT$$

$$L_2 \Delta i_{L2} = \left(V_{c1} - V_0\right) DT$$

So, this is during on interval.

Now we have to look at what happens during off interval. So, if I actually turn this off the inductance is still carrying the current, the capacitance definitely has to provide a path for whatever is the stored energy here that has to be dumped. So you are going to see that when I am looking at L_1, so diode starts conducting here to provide a path for the inductance, L_2's current. L_2 has to continue the current. It cannot abruptly stop conducting.

So, you will see that L_2 is essentially circulating the current like this. That is how it is going to be and as far as L_1 is concerned this is going to be the current path for L_1. So, this diode essentially provides the path like a diode in the boost converter as well as the freewheeling diode in a buck converter. So, it is providing a path for both.

So, in this particular case I have to write $L_1 \Delta i_{L1} = V_{in} - V_{c1}$. Rather this Δi_{L1} is decreasing. If I want, I can write this as minus because we know for sure that V_{c1} has to be greater than V_{in}. It cannot be less. So, I can rather remove the negative sign if you want and then I can write V_{c1} -V_{in}, either way is fine. So, this is corresponding to inductance 1's current, so inductance 1 is connected between V_{in} and capacitor.

$$-L_1 \Delta I_{L1} = \left(V_{in} - V_{c1}\right)(1-D)T$$

Then we will have to write about inductor 2.

So, inductor 2 is only withstanding whatever is my V_o, nothing more than that. So, I should be able to write $L_2 \Delta i_{L2}$, again if I put a minus I have to write minus V_o, that is it. Is that minus V_o? Because this is the current path, previously this was plus and this was minus, now when it is releasing the energy this will be plus and this will be minus.

$$-L_2 \Delta i_{L2} = V_0 (1-D)T$$

They are opposing each other, V_o and the inductance voltage looks as though they are opposing each other, they are in parallel actually. They are just in parallel to each other. So I should be able to equate now whatever is Δi_{L1}, similarly Δi_{L2}, It should be + V_o, I have written minus here. If this is minus, is this plus?

Let us see what happens. Because we will have to get ultimately this is a reverse polarity, as simple as that. So, let us try to take a look at here

$$V_{in}DT = \left(V_{c1} - V_{in}\right)\left(1 - D\right)T$$

$$\frac{V_{c1}}{V_{in}} = \frac{1}{1 - D}$$

exactly similar to the expression of boost. So, it looks as though my output voltage now for the boost configuration is V_{c1}, then that I am connecting it to another buck.

So, let us try to look at the second one, that is when we write about $L_2 \Delta i_{L2}$,

$$\left|\left(V_{c1} - V_0\right)DT\right| = \left|V_0\left(1 - D\right)T\right|$$

Of course, sign I have not taken care of. Sign has to be definitely in the opposite direction.

So, if I put a minus here, will it work? No, because this if I take it to the other side, they will not get added. So, I have let me write it in terms of magnitude, because I know for sure that it is reversing as far as the polarity is concerned.

So, let me write in terms of magnitude. So, I can say ,

$$V_{c1}D = V_0$$

Now using this and this, we should be able to derive the expression which will actually relate V_{in} to V_{c1} .So I can say,

$$\frac{V_{c1}}{V_{in}} = \frac{V_0 / D}{V_{in}} = \frac{1}{1 - D}$$

I am just writing here and writing from here, both. So, I should be able to say

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

which is similar to your buck boost converter. Of course, if I put a negative sign, I have to only remember that it indicates the polarity is in the opposite sense, that is it, nothing more than that. The polarity is exactly in the opposite sense. So, it is very similar to buck boost but it is basically a versatile converter more than any of the basic non-isolated converters because I have several variations that I can do and also the energy transfer mainly takes place because of the capacitance. And inductances generally are more difficult to design even at higher frequency as well as lower frequencies.

Inductances are even more bulky as compared to capacitances but generally, that is why in most of the integrated circuits they would like to avoid inductance completely if it is possible. You can somehow simulate an inductance by using something else, then that will be great but otherwise generally they tend to avoid the inductances as much as possible. Because here energy transfer takes place with the help of the capacitance this is considered to be much more versatile as compared to rest of the basic non-isolated converters.

So, so much so far, our D C to D C converters. So, we had seen mainly the basic 3 converters, buck, boost and buck boost, and then we looked at CUK converter just now and then we had looked at isolated converters which are basically 5 converters we had seen, flyback, forward, push pull, half-bridge and full-bridge. So, DC-D C converter is really not a very vast portion as much as rectifiers what we saw.

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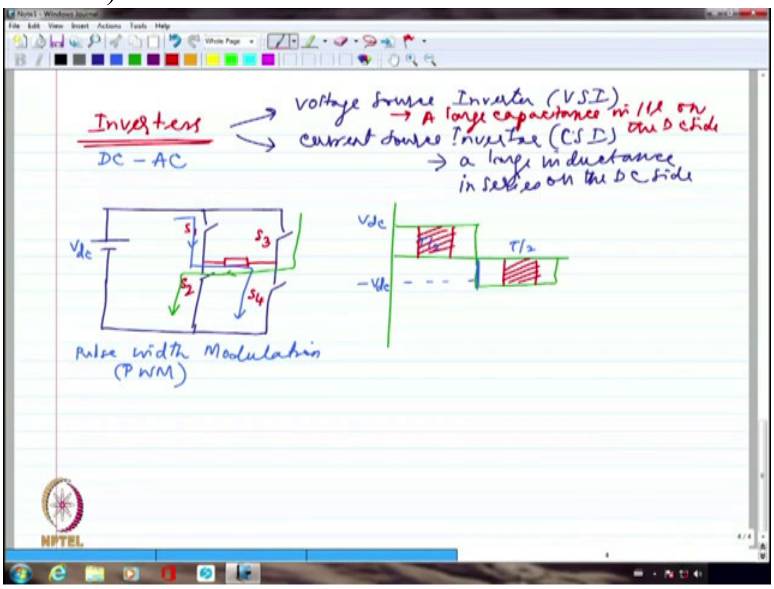

But the next portion what we are going to venture into, that is definitely a vaster, much vaster portion. Not probably again as big as rectifier. So, inverters, very clearly this is going to convert DC to AC and one of the most versatile circuits which are used everywhere literally. So, this invention of inverter has really propelled the induction motors to be used in all sorts of application.

Wherever we had variable speed requirement, induction motors earlier were not being used so much, synchronous motors were absolutely, because there was no scope to use it in variable speed application because we had only 50 Hertz and which could run only at a particular speed, nothing more than that.

So, when we want actually variable speed to be achieved, frequency necessarily needs to be changed, 120 f by p which is synchronous speed, so very clearly inverter once that has come into picture, we have had versatile applications for synchronous motor as well as induction motors. And synchronous motors normally have a better efficiency than induction motor because of which the variable frequency inverters have really made synchronous motor to be applied in several applications where it was a no-no, earlier.

At least induction motor has a small variation in the speed. Synchronous motor does not even have that when you have a constant frequency. So now synchronous motors are being used in many other applications where variable speed drives are important. So, the basic principle of inverter operation is whatever we had seen in full-bridge. For example, if I have one switch, second switch, third switch and fourth switch which I call as full-bridge inverter and what I have is a voltage source. So, we call these things as voltage source inverters.

There are two types of major inverters that we see. One is voltage source inverter and the other one is known as current source inverter which means the voltage source has to be necessarily converted into a current source by including a large inductance in series. If I put a large inductance in series, the inductance will not allow change in current so easily. So, it will look as though I have converted the voltage source into a current source because naturally there is no current source concept really it is available.

Everything is a voltage source, generally. Whatever we have is the voltage source. So, if I want to make it as a current source, I necessarily need to connect the very large inductance in series. So, V S I and C S I, current source inverter which is generally specified as C S I, so this will require a large inductance on the DC side. Similarly, I may require as a dual large capacitor on the DC side as far as the voltage source inverter is concerned. If I have for example a diode rectifier, I will have oscillating voltage.

I do not want to have oscillating voltage. I want to have a steady voltage. So, if I want the steady voltage I have to put a big capacitor in parallel. So here a large inductance in series on the DC side whereas here a large capacitance in parallel on the DC side. The two are dual of each other, basically.

So if I am having a circuit like this which is S_1, let us say this is S_4, this is S_2, this is S_3 and I connect the load here. In full-bridge DC-D C converter we had connected the primary of the transformer winding there. That is all is the difference whereas here I am directly connecting the load which will require the AC supply, maybe a single phase induction motor for example, right.

So when S_1 and S_4 conduct, I am going to have essentially a current this way whereas when I am going to have S_3 and S_2 conduct I am going to have current in the opposite direction, right? So by alternately turning on S_1, S_4 and S_2, S_3 I should be able to get alternating voltage across the load which is definitely not sinusoidal, agreed. It is going to be non-sinusoidal, no doubt. So, this is one of the voltage source inverter circuits which is very, very fundamental in terms of its functionality.

I can probably control the turning on and turning off these switches ultimately to arrive at, maybe sinusoidal voltage if I have some kind of special control technique which we will have to look at eventually. But if we assume that I am going to turn on S_1 and S 4 for 50 percent of the duration and I am going to turn on S_2 and S_3 for 50 percent of the duration, so this is $\frac{T}{2}$, this is also $\frac{T}{2}$. Of course, I will have a small dead band. Forget about that. That will be maybe only a few microseconds or something.

So out of 20 millisecond cycle, few microseconds I can neglect. That is Dead band I will require between these two, I cannot really have this on immediately. Maybe I will have to delay it slightly. This will give me actually, this voltage will be, if I say V_{dc}, this will be plus V_{dc} and this will be minus V_{dc}. So if I look at the RMS value it will correspond to V_{dc} itself. The

RMS value will be V_{dc}. So, I have mainly couple of disadvantages when I am going to make this like a square wave inverter. This is known as square wave inverter.

I am essentially having $\frac{T}{2}$ and $\frac{T}{2}$ positive half and negative half. I cannot control the RMS value of voltage. This is one of the major problems that I am going to have. If I have a fixed value of DC, I will also have a fixed value of output voltage. The second thing is, because it is square wave it is far from being sinusoidal, it will have so many harmonics. So, all these harmonics are going to create a problem especially if I am going to apply into a motor because motors require sinusoidal voltages and sinusoidal currents.

So, I am going to have the trouble of not being able to eliminate the harmonics and not being able to control the RMS value. That is why we have several control techniques called pulse width modulation which is PWM. So, we will use a lot of pulse width modulation control. What I mean is rather than having a pulse for complete 180 degrees, if I have a pulse only corresponding to this much; similarly, maybe I have a pulse only corresponding to this much.

For quite some time it is 0 voltage. I am going to have a pulse only starting from, let us say 45 degree and it will go until 135 degree for example.