Power Electronics
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Lecture 17
Isolated DC-DC Converters 1

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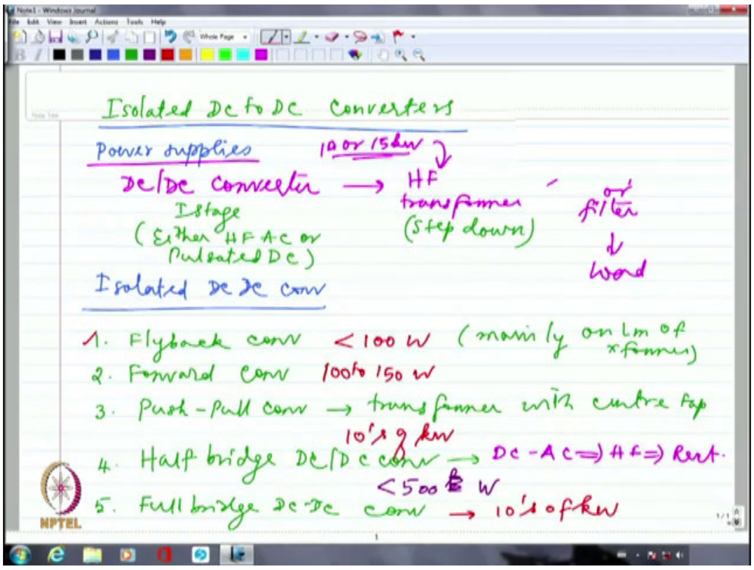

We are starting on isolated DC to DC converters. So isolated DC to DC converters as I told you will be normally used in power supplies, many of the power supplies use isolated DC-DC converter because the regulation becomes actually a twofold process. One is high frequency transformer which will step down at the load end and apart from that there will be DC to DC converter before that which will actually adjust the output voltage by means of duty ratio.

So first of all, the first stage is normally the DC-DC converter or which will have actually some kind of inversion process or pulsated DC production, so that this can be applied to a high frequency transformer. This is the way, normally it works. So this is the first stage, which will produce either a high frequency AC or it will produce the pulsated DC, whichever way it is.

Then it is being given to a high frequency transformer which will step down in all probability in most of the cases it will be step down. But what we get out of this may not be a perfect DC. So if it is AC, I need to necessarily use a rectification process. So in all probability, I may require a rectifier if not at least a filter or both. So I will require normally these as the multiple stages in an

SMPS. So these will be several stages that will be encountered normally in a switch mode power supply. It need not be always a switch mode power supply for a personal computer. It can be a power supply for a telecom tower.

Telecom towers which actually take your signals and put everywhere like it they are transmitting basically whatever is your mobile signal, it is all taken by a tower and from where it is being again propagated further. So these telecom towers normally will require power supply 24 hours a day, 365 days in a year. They cannot really face any power cut, it is not possible. So normally there will be a backup with a large capacity battery and those battery charging that is normally done by power supply configurations.

So what you get from the grid which is 230 volt 50 hertz AC, if it is single phase or 400 volts 50 hertz 3-phase AC that will be rectified. That will be going through rest of the stages of the normal power supply just now I talked about and then it will be charging a battery. So the final load in a telecom tower, if I try to look at what is the final load in a telecom tower for a large power supply? That will be of the order of 10 kilowatt, 15 kilowatt power supply, large power supply which will be charging the battery.

So that is not SMPS that is switch mode converters are used but definitely not of low capacity and high frequency transformer designed in those power supplies are really-really involved because you cannot expect saturation to happen. You cannot accept and you cannot really make completely leakage reactants free because if you make it leakage reactants free, there is a better possibility of saturation. You do not want excessive amount of losses, wastage of voltage. So it is a very-very tough design normally we have to go through for high frequency transformer, especially for 10 or 15 kilowatt rating power supply. It is not easy at all to design this high frequency transformer.

So telecom tower power supplies are typically one of the power supplies which use switch mode converters but which will be of larger rating to charge the battery, charge the battery in the telecom towers. Another typical application that is coming up lately is battery charging for electric vehicles. So electric vehicles normally, most of the electric vehicles run on battery. You have to have battery and battery normally on board charging becomes very difficult. On board charging means you have the battery sitting inside the vehicle itself and you try to charge.

So you have to essentially have the terminals of the battery really thick. The wires that are connected to the battery should be thick and it has to be done as quickly as possible because you do not want to hold on to the vehicle for too long. Let us say we create a charging station, you fill up petrol and go, normally that is the way people are envisaging. That the charging station should be, you just go, fill up your battery, top up your battery and go away. So that means it has to be done really fast. But really the designs are not so advance as of now.

It is very difficult, because if you have to charge a battery which is of very high ampere hour capacity, you have to send about 100, 150 amperes in one go, which is actually going to ask for very thick conductors. And it is not going to be easy, multiple vehicles being charged at the same time without causing any fire hazard, because huge amount of current, you can expect sparking and all those things. So that is the reason why people are talking about off board charging not on board charging, not on the vehicle itself.

You maybe charge a battery and keep it ready, take away your battery which is discharged and put the one which is already charged. So people are talking about these things. Not yet, it is a dream. Maybe it will come true pretty soon but, that is one of the major applications for battery charging used in power supply configuration. So apart from personal computers which use SMPS, a couple of other application I can right away think of is, one is telecom tower power supply, where you are planning to charge a battery there in the telecom tower itself to give 24 hours, 365 days power supply.

And the second one is electric vehicles battery charging, right PV battery charging. So if we look at isolated DC-DC converters, mainly there are several categories but we will look at a few of them and in that first of all we will start off with flyback converter. Flyback converter is only meant for less than 100 volt capacity because it heavily depends upon on the magnetizing inductance of the transformer that is we are going to use.

The high frequency transformer what we use in flyback its magnetism inductance is going to be the source of energy transfer mechanism. So this will be used only for about less than 100 watt, most of the times about 50 watts capacity, there ends the matter as for us. The application of flyback converters are concerned. The second type of converter that we will be looking at is forward converters. Forward converters is a slight modification of the flyback converter but only thing is we are not going to depend only on L_m.

Here we will depend mainly on L_m of the transformer, whereas here we are not going to depend only on L_m that is the magnetizing inductance of the transformer. So we will be able to go a little higher in terms of the capacity because even if L_m is not too high, there is a huge amount of leakage still we will be able to manage. I hope you remember your transformers. You have something called magnetizing reactance, you have something called leakage. Leakage is because of the air gap path normally.

And magnetizing reactance is because of whatever is the core that is offering us the path for the flux. So if we are having more leakage then flyback converter will not work properly that is what I am trying to say. Whereas, forward will be able to work even if there is little bit of more leakage.

So in this case, we will able to go between, say about 150 watts, so 100 to 150 watts is normally the capacity. Outer limit is about 200 watts we do not go beyond that normally. The third type of converter that we will be investigating, that is push pull converter. All of these, many of these at least not all of these, the last 3 that we are going to discuss all of them can work as inverters also, independently we will be studying them in inverters.

Push pull converter actually will use a transformer with center tap. So whatever we talked about as center tap rectifier will be very much applicable in this particular case. We will be using the center tap rectifier in this particular case, this can work for much higher rating. In fact, there are papers that are available of the order of 10 kilowatt or 12 kilowatt push pull converter. So people are using this extensively with solar PV applications as well.

So this is not just limited to the personal computer power supply. So this can go for at least 10's of kilowatt rating up to, it can go until that particular rating. At least there are research papers and some implementation that are available. The next one that we will be looking at will be half bridge. So half bridge converter actually will convert DC into AC and after converting it into AC it will pump it to a high frequency transformer and then a rectification process that is what is going to do.

So half bridge DC to DC converter will very clearly consists of DC-AC conversion stage then high frequency transformer and then a rectifier. These are the stages that will be involved in half bridge converter. But half bridge converter again is meant for a little limited rating we do not apply it for very large capacity cases because if I apply a particular voltage, I will get only half of that voltage as the output. And one more thing is the switch stresses become very-very large.

We look at this also, why the switch stresses become very large. So normally, we do not go beyond 500 watt capacity. We try to limit it to about 500 watts. Most of our SMPS that we use in PC all of them are made of half bridge normally. The output stage is half bridge.

Student: What is meant by stress across the switch?

Professor: Switch stress is how much is the voltage that it has to withstand and how much is the current, sudden jump in the current or whatever it has to withstand. The voltage stress will depend upon, when it is turned off, what is the voltage that is coming across? Because while it is turned on you are going to have very minimal voltage, so when it is turned off, what is the voltage that will come across the particular switch? That is what we mean by the stress across the switch.

The last one which is the counterpart of the half bridge that is full bridge DC-DC converter, this can again go for 10’s of kilowatt quite easily. This is also used very commonly in many of the solar PV conversion system as well as many telecom tower power supplies use full bridge converter where battery charging becomes mandatory. In those cases, generally full bridge converters are used extensively. And EV charging again people are exploring push-pull as well as this particular full bridge converter extensively for charging the electric vehicle batteries.

So full bridge has an enormous number of applications, so the rating in this case will be at least 10s of kilowatt as of now, maybe it can increase further because it depends upon if I use many devices in parallel some more devices in series, definitely I can increase the capacity. So those things are being explored quite a bit for these kinds of converters.

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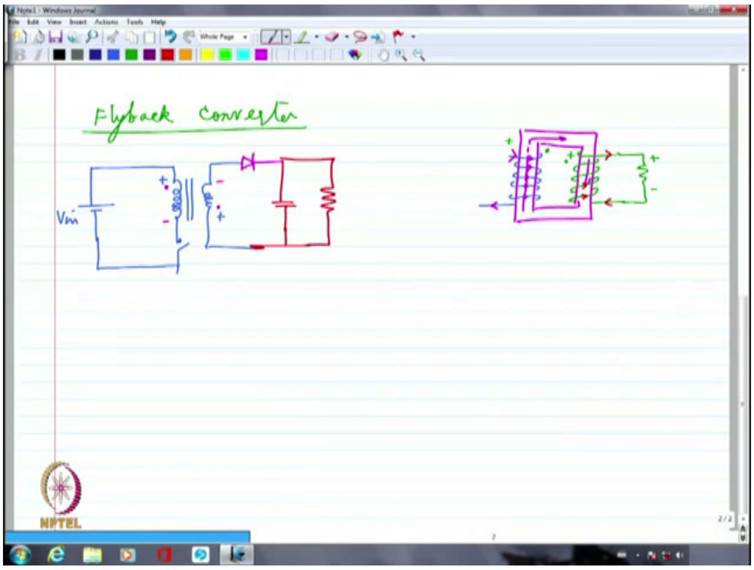

So let us now start with this flyback converter. I think there is one chapter in Daniel Hart completely dedicated to power supplies. That has all the isolated DC-DC converter topologies. I am going to confine myself mainly to the continuous conduction mode. So flyback converter normally the working in somewhat like this. First of all the circuit, this is the input supply which I want to convert into the output voltage which is at required value.

So I am going to have actually a transformer and then a switch. I can just show this as a switch which is actually a semiconductor switch which may be MOSFET or IGBT or whatever, one of them. And then this is closed through this and I am going to have the secondary here. Now if I say that this is plus here, when the switch is turned on, the transformer is going to be wound in such a way that this will be plus at that point in time.

So I can wind it in such a way I hope you guys remember the basic transformer principle. If I am having a core like this and let us say I wind something like this. And then this I am taking out. So let us say the current is flowing in this direction. It is flowing in this direction and it is coming out in this direction. So I am going to have essentially currents flowing like this, this is the way the current flows.

So which means, I am essentially looking at the flux oriented upwards. I hope so that I am telling this correctly. So it is upwards, so I am going to have the flux oriented upward. This is how it is going to be. So the flux here will be downward which means the flux that will be created by the secondary has to oppose this flux because if it is yielding, the flux will go to infinity. It cannot really go to very high value.

So the flux created by the secondary has to be exactly in the opposite direction. So let me again draw the winding arbitrarily. So let us say, this is the way it is and I am going to have the winding somewhat like this and then this will come out. Now you have to find out if I want upward flux, in what way my current has to flow? So the current has to flow in this direction, I hope so that I am again telling the direction correctly. This is the way the current has to flow.

If the current has to flow in this direction, so that means the current has to flow through this and it has to flow out like this .So I should have to connect a load, the secondary is normally connected to a load. So if I show a load, I have to show a load like this for example that means, this should be plus and this should be minus. Into the load always, the current will flow into plus and it will come out through minus. So if this is plus, I should say here this is plus and here this is plus. So I can say if I put a dot here, this is essentially indicating that wherever I am indicating the dot if the current is entering through that I should also say that it is again positive on the other side.

So I am essentially looking at the polarities of the similar nature and I would put the dot in those 2 points basically. So if i say plus and plus, I can put dot on both the pluses. If I put minus and minus, I have to put dot on both the minus. That is the way normally we are supposed to put the dot location. So if I say that this is my dot here. Normally we will have the dot located in the opposite direction as far as the secondary side is concerned. So the transformers have to be wound in such a way or they have to be oriented in such a way that this is the way it is.

Once I have a dots clear, then I should actually put a diode here. So on the non-dot terminal I better put the diode that is what I am trying to say. So if I am having the switch on because this is plus and this is minus, I will have this as plus and this as minus. So the diode will be reverse biased, the diode will not be forward biased, so diode will not be able to conduct whenever the switch is conducting. They are mutually exclusive, they will not essentially conduct at the same time. Now I am going to have actually a capacitor here and a resistor here.

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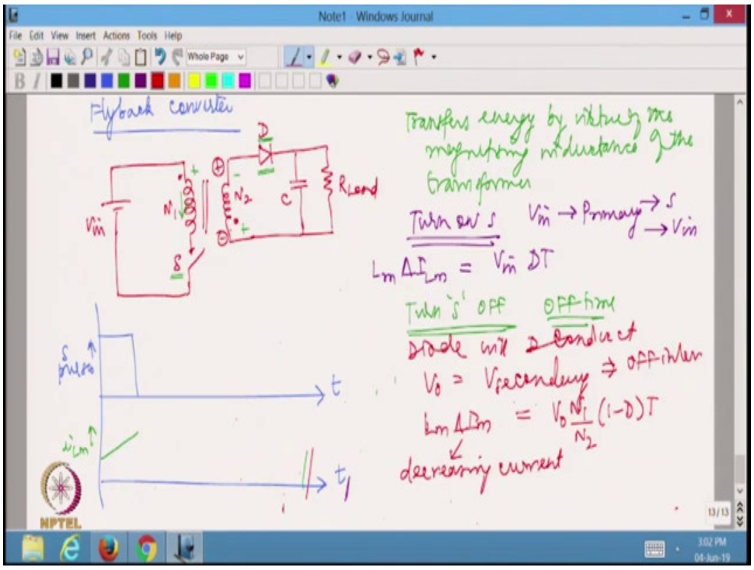

So we are looking at flyback converter, we have already drawn the circuit diagram. The output side has a diode, a capacitance and a resistance load. And the input side is having a switch and along with a transformer let us say this is the input voltage V_{in}. And let us say this is going to have N_1 as number of turns and this is going to have N_2 as the number of turns. This flyback convertor basically transfers energy by virtue of the magnetizing inductance of the transformer.

Please look at the dot notation here, whenever I am going to have plus here, I am going to have plus on this side and minus on this side. Which means this diode is going to be definitely reversed biased. So you can say that the switch S and the diode both of them are mutually exclusive. Both of them will not conduct at the same time. So we are actually, let us say, we are starting with when we turn on S. So, when S is turned on, we are going to have V_{in} ,then primary, and then S back to V_{in}, this is going to be the current path.

At that point, if I am try to look at how much is the stored energy, I am going to have

$$L_m \Delta I_{Lm} = V_{in} DT$$

We can draw the waveform somewhat like this. We are actually giving the a voltage which is V_{in} ,so this is the pulses for S. At the same time, if I try to look at how much is the current in the magnetizing reactance? I am drawing the waveform in steady state. So, I am going to have increase in the current like this, this is what is i_{Lm}.

Now let us say, I turn off S, so when I am going to turn S off, so this is going to be during off time of the switch. Because I am going to have the inductance carrying a current in this direction, it will definitely release its energy. When it is releasing its energy, I am going to have the polarities completely reversing like this. When the polarity is reversing diode D will conduct. When diode D is conducting, I will essentially have this particular voltage, output voltage will be equal to whatever is the voltage across the secondary. So this is during the off interval.

So, I am going to have essentially $L_m \Delta I_{Lm}$ which is actually in the reverse direction, this is decreasing current because the inductance is releasing its energy.

$$L_m \Delta I_m = V_0 \frac{N_1}{N_2}(1-D)T$$

So I should be able to equate them as follows.

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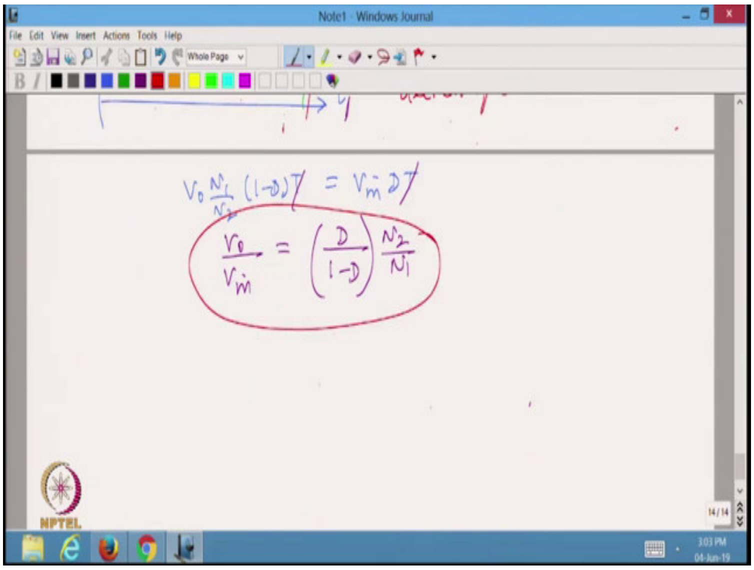

$$V_0 \frac{N_1}{N_2}(1-D)T = V_{in} DT$$

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

So this is going to be the input-output relationship as far as flyback convertor is concerned.

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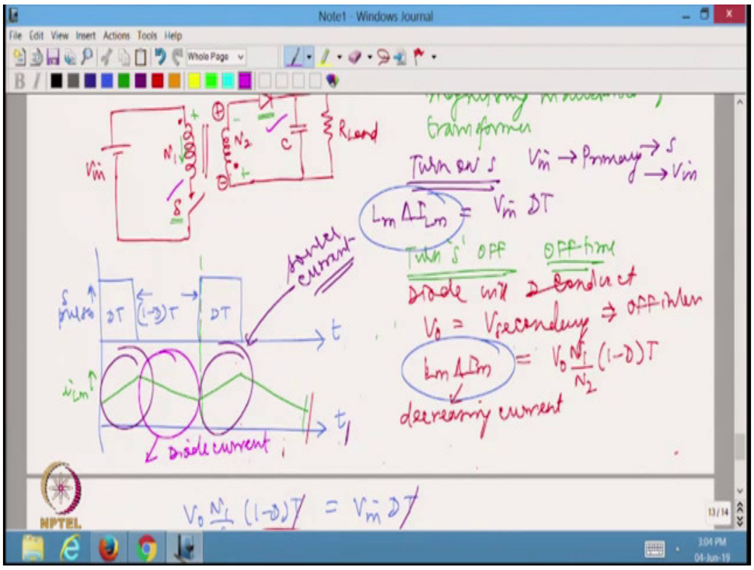

And if I try to draw the waveform here further, I will have actually during off interval it is going to again fall. Again on interval, it is going to increase, fall, this is how it is going to be. Correspondingly, I should draw the pulses here. So I am going to have this pulse again coming up for a duration which is corresponding to this. So this is DT this is also DT whereas this is going to be $(1-D)T$. So, one major problem of the flyback convertor is if I try to look at the input current I have only this portion as the input current, this is what is the source current. So source current will be discontinuous in this case. Inductor current looks like it is continuous but please note this portion of the current is going to be diode current.

This is actually the diode current, so we will not have the diode and switch conducting simultaneously, so the input as well as output currents if I try to look at the device currents they are discontinuous.

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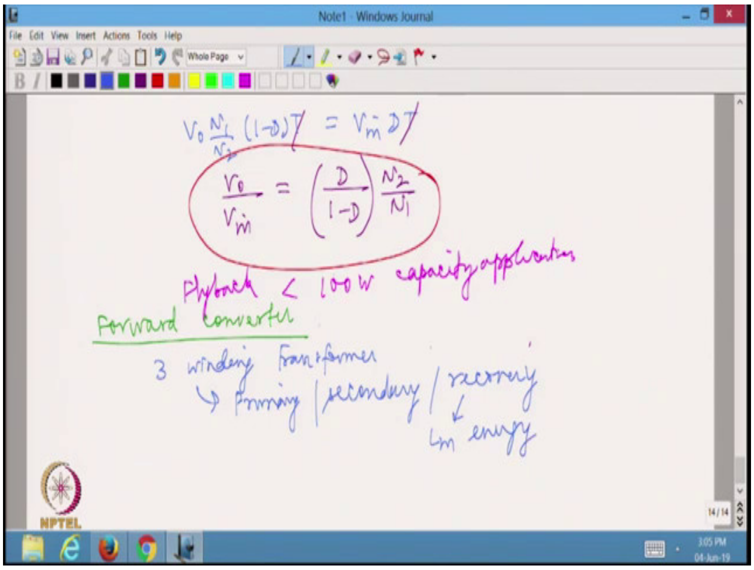

That is one reason why generally flyback convertors are used only for less than 100 watt capacity application not more than that. Now let us move to the second type of convertor which is known as forward converter. In flyback converter the magnetizing energy was used to transfer energy between the input and output side. Whereas in forward converter we are going to have a little different mechanism, so forward converter is going to have a 3 winding transformer, one of the winding is generally known as the recovery winding. So primary, secondary and then a recovery winding. The recovery winding is the one which is going to allow the energy stored in L_m to be dissipated. So this will be dissipating or circulating L_m energy.

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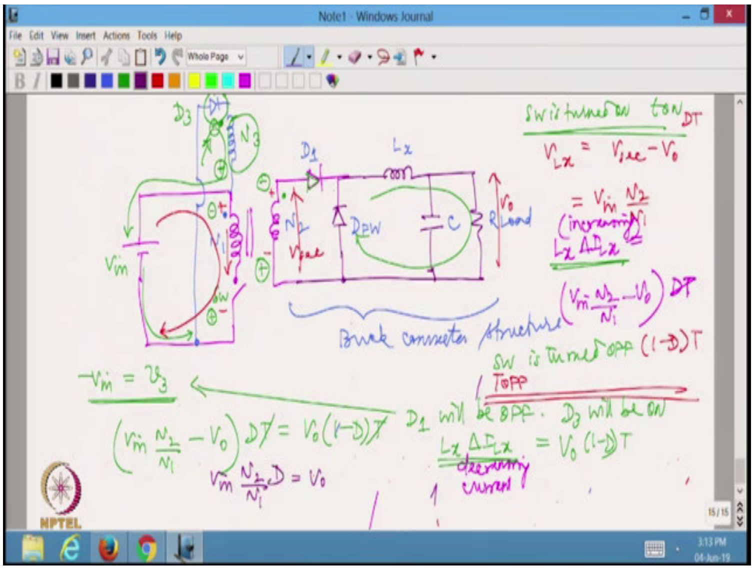

So let us now try to draw the circuit of the forward converter. So in the forward converter again I am going to have a primary which is connected to the source through a switch and I am going to have actually a secondary. The secondary is going to have one diode and I am going to have one more freewheeling diode and then I am going to have inductance which is going to smooth out the current. Then I am going to have a capacitor and I will have a load.

So please note that this particular structure is very-very similar to buck converter. So there is hardly any difference between a buck converter and the output side of this. Let me call this as DFW similar to a buck converter. Let me call this as some D_1, this is N_1 turns and let us say this is going to have N_2 turns and let us say this is the inductance which is going to function as the buck inductor in the case of a normal buck converter. This is the capacitance which is going to filter the output voltage and this is the load.

Now I am going to have a recovery winding also, so the recovery winding is here and I am going to have essentially a diode connected like this. And which is actually coming to this. Now let us say I am going to have basically a dot here. So this is going to be having a dot here and the dot for this is also going to be here. And the dot is here for this particular secondary.

Let us say this is V_{in} ,now let us say my switch S_w is turned on. So, during the t_{ON}, let us see what happens. We are going to have a current which is flowing like this, through the primary like this.

During that time, I am going to have an induced EMF in the secondary side which is going to have plus here and minus here. So I should be able to say if this is V_0, the voltage here if may call this as V_{sec}, I am going to have,

$$V_{Lx} = V_{sec} - V_0$$

$$= V_{in} \frac{N_2}{N_1}$$

And this is going to persist for a duration of DT which is corresponding to t_{ON}. So now I can write $L_x \Delta I_{Lx}$ whatever is the increase in the current during on interval, $\left(V_{in} \frac{N_2}{N_1} - V_0 \right) DT$. So this is going to be the equation corresponding to on interval.

Now let us say S_w is turned off, this will persist for a duration of $(1-D)T$. So let us look at what happens during t_{OFF}. So, during t_{OFF} ,if I try to look at the functionality of this circuit, please note that already magnetizing energy is stored, so I would have had a current in this direction and I have had plus here and minus here. Now this energy is going to be released, so I will have the reversal of this polarity. This will become minus and this will become plus.

So I am essentially going to have this becoming minus and this becoming plus, so the diode will start conducting. If the diode conducts, please note I am going to have actually the current flowing in this direction. So it is essentially flowing in this direction it will flow like this. So it is flowing into actually the positive terminal of V_{in}. So, I will have $-V_{in} = v_3$. This is going to be the state and as long as I am going to have the current flowing and the voltage here or the energy stored in the inductance is able to forward bias the diode.

So I am going to have essentially under this condition, this diode will not be able to conduct because this has become minus and this would also have become minus and this would have become plus. So D_1 will be off but D_3 will be on. If I may call this as D_3, D_3 will be on. Now I am going to have the voltage relationship of the tertiary winding like this. Now I can write this will be the path for the current as far as the secondary side is concerned. So, I am going to have $L_x \Delta I_{Lx}$ where this current is decreasing, so I am going to have decreasing current.

Whereas here it will be increasing current, so this decreasing current is going to be equal to $V_0(1-D)T$. Now I should be able to equate this and this together, so let me write that

$$L_x \Delta I_{Lx} = V_0(1-D)T$$

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

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

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

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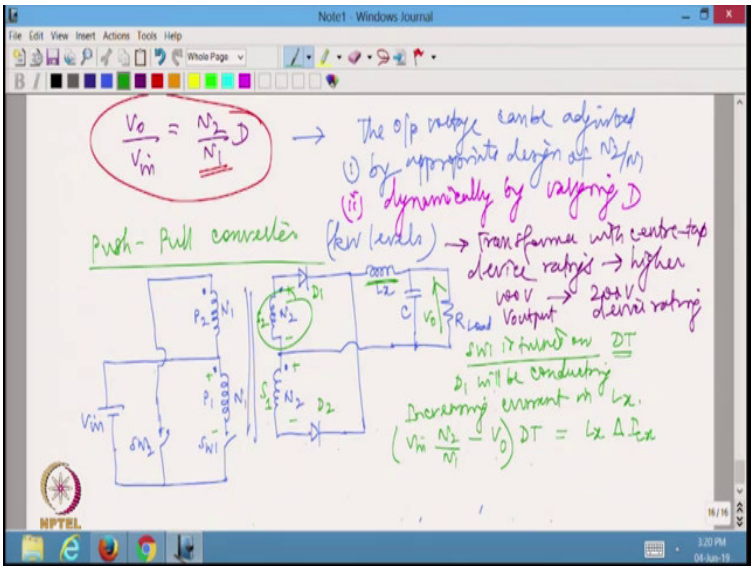

You can very well see that the expression is very much similar to the buck converter except turns ratio of the transformer. So we will be able to adjust in many of the isolated DC-DC converters, the output voltage can be adjusted right by appropriate design of N_2/N_1 this is one way. The second way is it can be dynamically adjusted by varying the duty ratio. So we are having definitely more degrees of freedom whenever we are looking at the functionality of an isolated converter.

The third converter that I want to take up today is push-pull converter. The flyback converter we said is only good enough for ratings less than normally 100 watts. Forward converters probably is good enough from up to 150 to 200 watts. So it is available for little larger rating. But if I look at push pull converter, push pull converters are available even at kilowatt levels. This is one of the major advantages of push pull converters. Only disadvantage is, I will require transformer with center tap and device ratings will also be higher.

Device ratings normally will be higher. What I mean is, if it can deliver only 100 volts, the device that will be chosen will be for 200 volts rating. So this is the output voltage whereas this will be device rating. So device rating will be twice the voltage of the output magnitude. Let us draw the push pull converter. So let us say this is my source that is available and I am going to have one transformer winding like this which is going to have a switch connected like this. So, let me call this as P_1 and let me call this as S_{w1}, which is switch 1.

So this is one of the switches. I am going to have one more primary which is with a center tap. So two primaries you can say which are connected together with same number of turns. If I am going to have N_1 turns here, this is also have N_1 turns and this is going to be called P_2.Now this will also be connected with the help of another switch to the negative terminal of the voltage source, let me call this as S_{w2}. As far as the secondary side is concerned, I am going to have actually a secondary winding here again with the center tap.

So let me call this as with N_2 turns for each of them, let me call this as S_2 and let me call this as S_1. Now let us say I have connected diodes here, so this is like a center tap rectifier configuration which we had studied earlier. So this will be center tap rectifier. And I am going to have from here, the load connected, of course it will be connected through an inductance, a capacitor filter and ultimately the resistive load. So, let me call this as L_x, let me call this as C, and this is R_{load}. Now let us try to look at the working. Let us say the dots are somewhat like this. This is going to be the dot and let me probably put this as the dot. So I hope so that the dots whatever I am assuming are correct that is all.

Now I am going to have essentially this particular thing is V_{in}, let us say primarily first of all S_{w1} is turned on. So it is actually turned on for a duration of DT, this is going to be the duty ratio, DT. So S_{w1} is turned on for DT, under that condition I am going to have essentially V_{in} coming across P_1. So I will have plus here and minus here. So the same way I will have essentially plus here and minus here. Similarly, I will have plus here and minus here.

So correspondingly if I may call this as D_1 and this as D_2, D_1 will be able to conduct. And I am going to have energy stored in L_x. So, I am going to have increasing current in L_x. So I can say $\left(V_{in}\frac{N_2}{N_1}-V_0\right)DT = L_x \Delta I_{Lx}$,this is during the on interval of S_{w1}.

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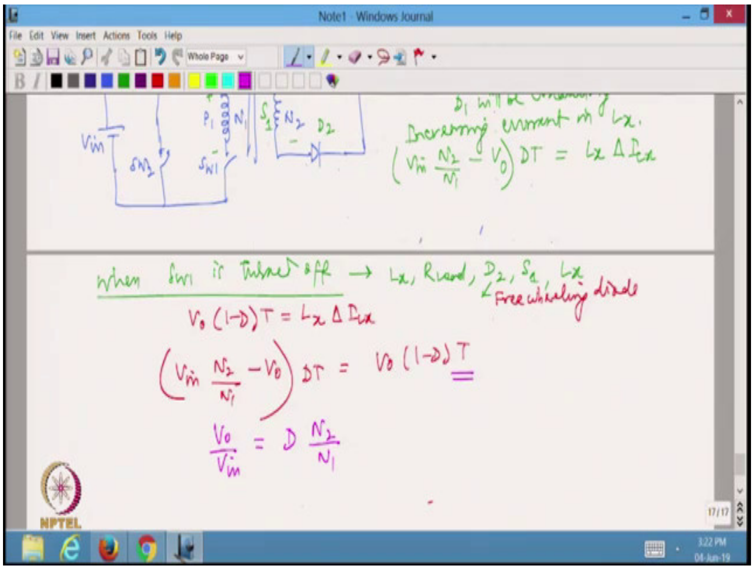

Now if I try to look at what happens when I turn off S_{w1}. So when S_{w1} is turned off, I am going to have essentially this L_x originally it was carrying the current in this direction, so this was plus and this was minus. Now I am going to have exactly this reversing its direction. So I will have now, plus here and minus here. Voltage will actually reverse its direction, current will continue in the same direction. Now let us see, if the current flows in the same direction, it should be able to flow like this, flow like this and complete the path.

So now D_2 can act like a freewheeling diode, so let us just try to look at the path. The path is going to be through L_x, it is going to go towards R_{load}, from R_{load} it is going to be through D_2 and then it is going to be through S_1 and back to L_x, so this is one of the path, please note that this itself is functioning like a freewheeling diode. So it is working perfectly fine. During this condition, I can say $V_0(1-D)T = L_x \Delta I_{Lx}$. So now these two can be equated.

When I equate them, I should write

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

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

But in this case, until now we have analyzed it not for the entire T duration, this is only corresponding to T/2.

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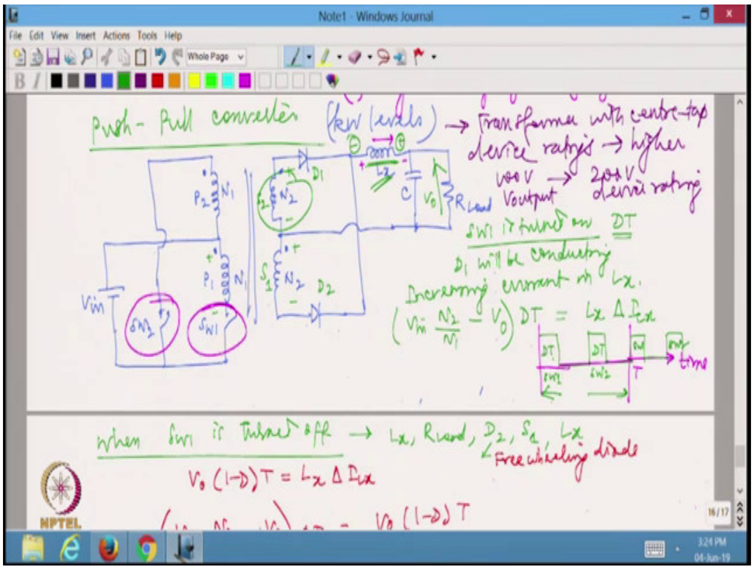

What I want to say is that, if you look at this entire operation, S_{w1} is going to be operated for $D\frac{T}{2}$. And S_{w2} will be operated for $D\frac{T}{2}$. So if I draw the wave forms I should show it as though if this is the total T, I am going to have for DT this will be turned on for S_{w1} then for some time nothing is going to be turned on. Then again for DT, I am going to turn on S_{w2} and then nothing will be turned on. So I should rather show this as T just a second. So I have to show this as T, this is what is T, so this is the time I am plotting. So this corresponds to one cycle. Again it will repeat itself, Again I will have S_{w1} turned on then S_{w2} turned on and so on. I am going to have this repeated. So I will have within 1 cycle itself, 2 times I am going to have energy stored in L_x.

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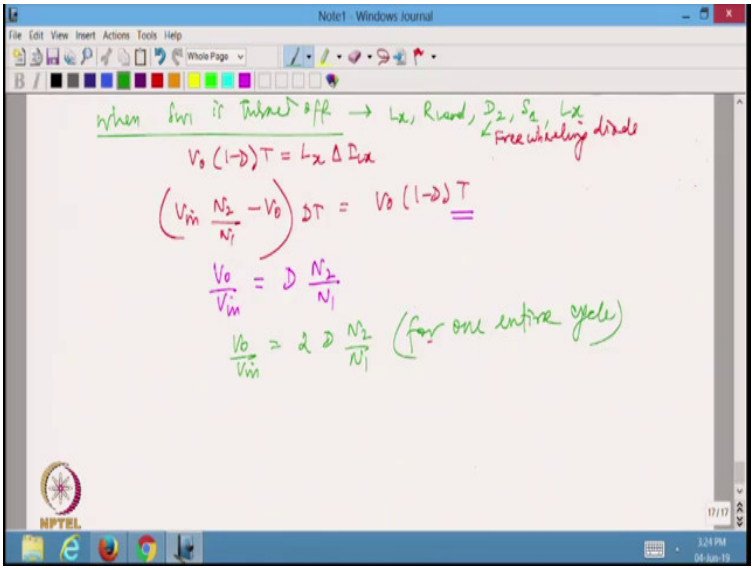

Because of which I should be able to say in all probability

$$\frac{V_0}{V_{in}} = 2D\frac{N_2}{N_1}\text{, for 1 entire cycle.}$$

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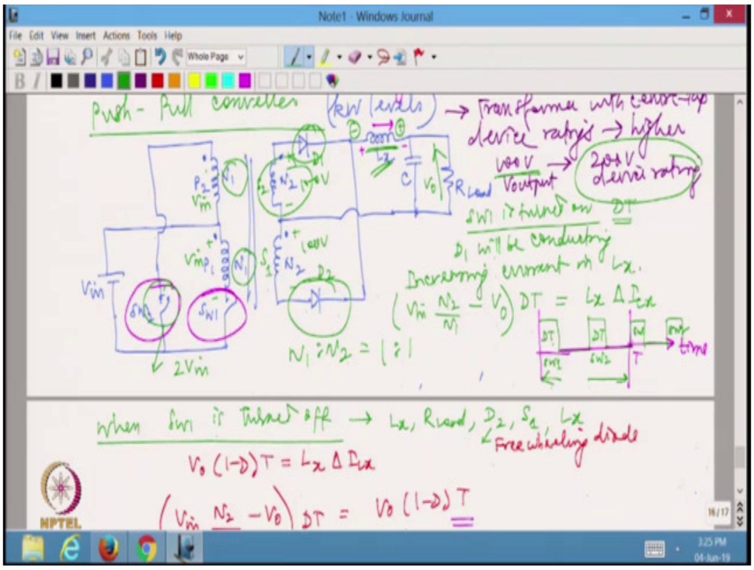

One more thing that we will have to realizes is that what I am applying here is V_{in}. So when S_{w1} is conducting, I am going to have this carrying V_{in} but the same voltage is going to be induced on the other side also because this is also having N_1 turns.

So, I am going to have clearly V_{in} coming into picture here also. So because of this together, whatever I see here will be $V_{in} + V_{in}$ that will be $2V_{in}$ so this switch has to block $2V_{in}$. This is what I meant, if the output is 100 volts, I will have the device rating to be twice that value. The same is the case here also, if I say that $N_1 : N_2 = 1:1$. Then if I have 100 volts induced here, this will also have 100 volts. So this one device is conducting, I can say the other device will have to block a voltage of 100 plus 100 which is equal to 200 volts.

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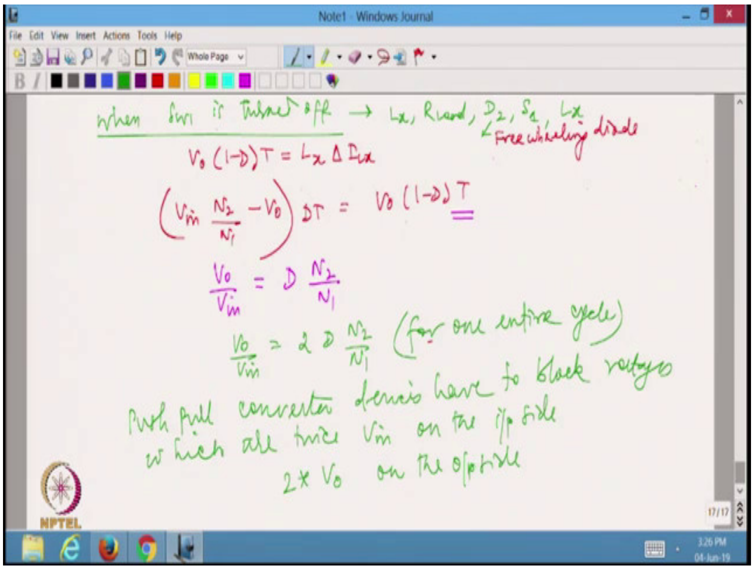

So, in this particular case, the push pull converter devices have to block voltages which are twice V_{in} on the input side and 2 V_0 on the output side. So what we have seen so far is three kinds of isolated converters, one was flyback, the other one was forward, the third one was push pull. Please revise this, we will be looking at two more converters in the next class which are half bridge and full bridge. Apart from that, we will also be looking at CUK converter or cut converter which can work as a buck boost converter. So please revise these 3 converters. Thank you