

# CHARGING INFRASTRUCTURE

Prof. Apurv Kumar Yadav

Department of Electrical Engineering

Indian Institute of Technology Roorkee

Week-07

Lecture-31

## Lec 30: Revisiting Isolated DC-DC converters-II

Hello everyone, welcome to lecture number 31 of this NPTEL lecture series on charging infrastructure. In this lecture, we will discuss further details on isolated DC-DC converters. In the recap, we have seen the forward converter and its operation. We have understood there are some limitations, for example, in this converter, since we have reset of the core, we must provide sufficient time in which our core flux resets to 0 value. That's when we need to give a sufficient  $(1 - D)T_s$  period. This also indicates we have a limited duty ratio, as you can say.

In other words, we can say we have also limited our switching frequency. We cannot go to higher frequencies because if you go for a higher frequency, then my  $T_s$  will be smaller, and since my  $T_s$  will be smaller, my  $(1 - D)T_s$  will be smaller. So, my core flux may not reset completely. That is why it will limit the smaller value of  $T_s$  to which we can go, and that is when it will limit the switching frequency. Then, in this case, since we have diodes switching in every cycle, we have a significant amount of reverse recovery losses of the diode, which will add to the overall losses of the power converter.

Since the flux in the core resets through this  $R_f$  resistance, we have a lossy reset of the transformer core, and that's when we also have other losses like  $I^2 R_f$  losses across this resistance  $R_f$ . We have also seen that since my flux goes from 0 to the maximum value and returns to its initial value 0, it is not going in the negative direction. So, the core utilization is limited to nearly half. Why do we say core utilization is limited to half? Because we have  $V = N \Delta V A * f$  of operation since my frequency if we assume frequency constant, is my N constant, B constant, then in this case we are going from 0 to

some  $B_{max}$  value obviously this  $B_{max}$  value is lesser than the maximum value which the core can go maximum flux density value with the core can go so since we could have gone to  $-B_{max}$  negative value of  $B_{min}$  to  $B_{max}$  value so we could have gone to  $-B_{max}$  value to  $+B_{max}$  value and that's when we could have reduced the size of the core by half since we are going from 0 to  $B_{max}$  value we are actually use you know our only the half the core or we can say that the area is kind of doubled in this case so we can say that the core utilization is limited which is nearly half so for example if we write since here we go from 0 to  $B_{max}$  value so our area of core here is nothing  $\frac{V}{2NB_{maxf}}$  and if we would have gone if the  $\Delta V$  would have been from  $+B_{max}$  to  $-B_{max}$  then we could have written the area of the core to be  $\frac{V}{2NB_{maxf}}$  because it goes from  $-B_{max}$  to  $+B_{max}$ . So that will give me my area of the core to be half. We lose by half I mean so that's why we are having the lower core utilization we could have utilized the toys the core size but in this particular converter we are just using half of the core that's why core utilization is limited and when the switch is off it is actually blocking a good amount of voltages higher than the input voltage so that's when this voltage rating of the switch is very much higher now one another forward converter configuration is there which is forward converter configuration with demagnetizing winding so forward converter with demagnetizing winding now in this converter if you look very carefully we have instead of having single you know two windings we have now three windings here the dot is here with a dot is here and, in this winding, we have primary winding with  $N_p$  turn secondary winding with ascent when ns run and the winding having the diode with the number of turns to be equal to  $N_d$  and if you look very carefully in this case again the same thing will happen. We have  $DT_s$  period. We have  $(1 - D)T_s$  period. Now let us see what will happen, let us say this is  $V_p$ . Here we have Vs coming over here. Now, in this case, whenever my S1 switch is on in the DTs period, the voltage across the primary winding is directly the  $V_{in}$  voltage which we have written down here  $V_{in}$  voltage you can see here the  $V_{in}$  voltage is here in DTs period S1 is on because of  $V_{in}$  voltage we have here applied on this secondary side positive voltage  $\frac{N_s}{N_p} * V_{in}$  voltage appeared over here, and because a positive voltage appeared over here, this diode is forward biased. And because this diode is forward biased, this diode will get reverse biased.

And the current will be actually flowing through the inductor to the load. And if we do the KVL in this loop again during DTs period, the

$$v_L = (nV_{in} - V_o)$$

Same as that what we have seen in the previous versions of forward converter. and again this windings are again all the three windings are wound on the same core so all the three are magnetically linked together now so during this point when whenever i am applying the wind across this winding at this place we are actually applying you know we are applying positive negative so we are actually applying not meaning actually we are applying  $\frac{N_d}{N_p} * V_{in}$  being voltage here, so because of that, this diode gets reverse bias because we are having we are applying some positive potential onto the cathode of this diode, so we have here this diode is reverse bias.

Since we have reverse bias and we have only one winding, so the flux in the core will actually be rising linearly with upward thing because we have positive voltage applied with the slope nothing but equal to  $\frac{V_{in}}{N_p}$ . And if we see the voltage across DS1, whatever the voltage of DS1 we will get, we will get voltage across  $\frac{N_d}{N_p} + V_{in}$  which is applied across the DS1, so let us say this is with this polarity, so this is with  $V_{DS1}$ . The voltage across this one is in this loop. If you do this in this loop, then it is minus n minus coming over here and  $\frac{N_d}{N_p} * V_{in}$ , which is coming over here now Now, we will see if we look very carefully the idle S1, this current, there is no current which is flowing through here. So, that is why we can say this idle S1 is equal to 0, 0 we can say.

So, this is what we get in and since our switch is on, so this voltage across switch is 0. now in  $(1 - D)T_s$  period, and since my S1 switch is open, what happens is that suddenly the current from here, which is flowing over here was sees the  $-\frac{di}{dt}$  Because of this  $-\frac{di}{dt}$ , this polarity will get reversed because of this reverse Because this polarity is reversed, what happens is that this diode is reversed biased and since this diode is reversed biased, the current,  $I_L$  current which is going over here has to find a pathway. It will find a pathway to D2 and that's when D2 is forward biased. And the voltage in  $(1 - D)T_s$  period, the voltage across

$$\text{output inductor is } v_L = -V_o$$

And that is when we can ensure the volt-second balance of this inductor, and that is when we will get the same value  $V_o = NV_{in}D$ . However, if we look carefully however the other side converters look I mean the third winding which is the winding which is connected through the diode DS1, what does it look like. So, since we are now having the negative polarity across this so because of this negative polarity, we have in this way, we have negative polarity, which comes like this since we have come like negative polarity like this here also we have negative

polarity dot will become negative since the dot will get negative this diode will get forward biased and since this diode gets forward biased we have you know current drawn from the source in such a manner that The flux will be falling down because see when we turn on this diode, in order to find the path, there will be current, which will be drawn in such a manner that we will be now applying the voltages in such a manner that we will have the current going from here to here. and the voltage applied across the core is nothing but  $-V_{in}$  voltage, which will be applied, and that's when the flux, which will be there, is nothing but dying down with  $\frac{-V_{in}}{N_d}$  voltage, because if the diode is forward biased, if this is now forward biased

So, what happens? The  $V_{in}$  will now apply across this winding  $N_d$  and since the dot polarity is such that the flux which have gone to some maximum value will be now falling down because since all the windings are bounded on the same core, the flux in the core will now have the negative slope and it will now die down to 0 value and it will die down with the slope  $\frac{-V_{in}}{N_d}$ . Now, since we are applying  $V_{in}$  voltage over here in this direction, what happens is that on this side, we have  $V_s$  voltage, which is applied in this direction to be nothing but equal to  $\frac{N_d}{N_s}$  into, I am sorry,  $\frac{N_s}{N_d} * V_{in}$ . and on this side, we have the voltage

$$V_p = \frac{N_p}{N_d} * V_{in}$$

So if we do the do the KVL on this loop what we have is we have the voltage which will be appearing across  $V_{S1} = V_{in} + \frac{N_p}{N_d} * V_{in}$  voltage appear across this switch because in this one we have  $V_{S1} = V_{in} + \frac{N_p}{N_d} * V_{in}$  in this loop KVL loop if you do and that is what we have seen over here, and in the primary side we are now having a voltage  $-\frac{N_p}{N_d} * V_{in}$  applied over here and that is when we will see our flux in the core gets die down with the slope

$-\frac{N_p}{N_d} * V_{in}$  and since the diode is forward biased we have nearly zero voltage or some forward negative forward voltage will be there but that we assume to be nearly negligible so it is zero. And since we are having the flux which is actually dying down. So what we have is we have now the current to the magnetizing branch will be dying down using the  $I_{DS1}$ . And that will be nothing but  $I_m$ . which was there previously because the current in this one will go to this. So,  $I_m$  is corresponds to this  $I_m$  is corresponds to  $\Phi_m$ .

that means the current required to magnetize the core of the transformer which is let's say some peak value of current  $I_m$  it is going so that current will now be falling down since here it was  $I_m$  it was flowing beforehand so now what happens is that in this one through this winding it is actually nothing but this  $I_m$  which will be send on to that side which is nothing but  $N_p * I_m$  divided by  $N_d$  because we do  $N_p * I_m$  to be current which is going through the  $I_{DS1}$  times  $N_d$  and that is what we have written over here this is the value this  $I_m$  is nothing but this peak value what we have it is not the slope it is the peak value what we have this  $I_m$  times  $\frac{N_p}{N_d}$  where  $I_m$  is the magnetizing you can write  $I_m$  magnetizing component of which actually lead to which led to  $\phi_m$  flux so because flux is nothing but  $n$  times  $i$  so if we have some  $i$  so there will be some flux corresponds to this so the  $i_m$  is corresponding to that flux  $\phi_m$  is the maximum value of flux the core will go so this is one interesting configuration forward converter where we are actually resetting the core using another winding connected in this manner now here the disadvantage with this topology is obviously we have multi winding transformer so we have to wind one more transformer winding we can say that multi winding transformer second obviously limited switching frequency because we must ensure that

We must ensure that this will die down to 0. This flux should die down to 0. We must provide some fixed amount of time during which this flux will die down to 0. So, that is why we must have some sufficient  $(1 - D)T_s$  period. So, that is why we can say that we cannot increase our switching frequency beyond a certain point.

Otherwise, the  $(1 - D)T_s$  period will be very less. Now the third point what we will get is now we have forgot to see one more thing since here negative positive is there we are having  $V_{in} + \frac{N_p}{N_d} * V_{in}$  and let's say the flux goes to 0 at this point. When the flux goes to 0 at this point what happens is that this diode on this winding having  $N_d$  turns will now which is connected across that will now cease to conduct since it ceases to conduct what happens is that There is no  $V_{in}$  voltage which will be applied across the winding. That's when there is a zero-voltage applied across this primary winding and that's when the switch will now block only the  $V_{in}$  voltage across this which is what we have seen over here.

And voltage across this diode is also this  $V_{in}$  because if you do this particular loop, it is the same  $V_{in}$  voltage which will be coming across this diode and that diode is reversed by itself. It is actually blocking the  $V_{in}$  voltage, the DS1 voltage. So that is what we will see, the  $V_{in}$  voltage

$V_{DS1}$  across  $V_{DS1}$ . So, we can reduce this number of  $N_d$  turns to increase the slope and that's when we can die down faster. During that time, we will increase the voltage rating of the switch.

So, that's a trade-off we have here. So, what we can say that here again, the switch S1 rating is greater than mean input voltage again this is the thing fourth point again since the flux is going from zero to maximum and maximum so we can say that transformer is underutilized nearly half time by half time half of this is underutilized by by nearly half time and fifth point we can say that here again one important thing which we did not discuss here is whenever See, every winding will have its own. We just remove this part.

Every winding will have its own leakage inductance. and this leakage inductance is not the inductance which is actually coupled with the other winding it is the inductance which is associated with the same winding so now the problem is whenever you open this s1 some current which is flowing through here ip current flowing through this primary winding so some current is going through this winding now during this time what happens suddenly you turn now open this S1 switch so the things which is actually coupled will now actually move to the next winding however if we look very carefully there is also the leakage component which is there and that leakage component will actually generate since we are  $-\frac{di}{dt}$  we have  $-L\frac{di}{dt}$  voltage which will be coming across this inductor and that will have some some peak value which you will see at the peak of this one this junction which is something like this which looks something like this let me draw with that color which will look something like this at the initial period it will have something like this that means the voltage will look something like this then comes over here and then comes over here this is my  $V_{in} + \frac{N_p}{N_d} * V_{in}$  and this is the voltage kick which we will get due to the leakage  $L_{lkg}$  of this finding so the fifth point which is associated with this configuration is only the voltage kick on this we can say extra voltage the voltage keep on switch S1 due to leakage inductance so this is another disadvantage which is associated with this with this configuration of forward converter now so this particular this voltage kick also we can remove by using the dual switch forward converter which is another configuration of forward converter let us see the dual switch forward converter so in this particular converter what we have is we have S1 switch we have diode over here and then we have another diode and then another switch S2 switch and this is nothing but winding  $N_p$  winding  $N_s$  winding and on the secondary side. Again, it's the same thing C, L, D1, D2, and this is nothing but diode let us say DR1 let us say DR2. So, in this particular case during DTs period when we during DTs period here again  $V_{in}$  voltage is applied during DTs period S1 and S2 is on.

When it is on the  $V_p$  what we are applying over here is the  $V_{in}$  voltage that is when here  $V_{in}$  voltage will come and the voltage across  $v_L = (nV_{in} - V_o)$

because this diode D1 is forward bias this will be reversed by D2 will be reversed by and when we will turn off this S2 switch what happens is that since the current direction is here the current will be flowing in such a manner that it will actually keep on flowing in this direction and this direction will be such that if we go here then comes back to this place like this And since these diodes are turned on, what we are doing is here we are applying minus  $V_{in}$  voltage because we are applying minus  $V_{in}$  voltage here and minus  $V_{in}$  voltage over here. Here we are actually applying  $-nV_{in}$  across this secondary winding and that's when this diode is reversed by, since this diode is reversed by the current which is flowing through this and we can say in  $(1 - D)T_s$  period. we can say S1 and S2 is off and since it is off we can say voltage through inductor is nothing but minus 0 and if we do volt second balance across the inductor L volt second across L.

If we do, we will get nothing but  $V_o$  to be  $nV_{in}$  same thing and  $V_{in} * D$  because it is having the same voltages across this inductance L in both the sides. So, this is also one way by which we can actually, you know, obtain the forward converter. And again, here is the same thing we are having. We are having the... you know flux going from 0 to 5m and then coming back to 0 and see here when the current goes down to 0 automatically this diode will be reversed by us and that's when we have now applying 0 voltage from this primary winding and that's when the flux will be going from 0 to 5m and then coming back to 0.

So, this is what in this case it is going by  $V_{in}$  by NP slope in this case it is going by

$V_{in} - \frac{V_{in}}{N_p}$  slope. So, this is you know this is DTs period and this to this period or if we this is  $(1 - D)T_s$  period and after this point it is 0. Here again, we must provide some  $1 - D$  period duration. So, we have limited switching frequency, we have limited co-routers, same as what we have, you know, discussed in the previous configuration. However, in this case, the core reset is happening losslessly and there is no voltage kick you will see across these devices S1 and S2.

whenever the switches turn off and here in this case the S1 and S2 switch is actually blocking i mean voltage rating is nothing but equal to  $V_{in}$  here the voltage rating is same but uses but it uses two switches two switches and two diodes in primary side Which are you know some of the

disadvantages of this forward converter. And again, we have limited switching frequency. We have reverse recovery losses due to D1 and D2. and the core utilization is half all these disadvantages still persist with this configuration of forward converter so now if you look in case of forward converter.

We are under utilizing our core as the flux density is going from zero to positive maximum value that means  $B_{max}$  and then comes to zero. We are not going in negative flux density region that means in the third coordinate of BH loop and if we could have made our flux density swing from  $+ B_{max}$  to  $- B_{max}$  then we can increase the core utilization. So let us see the converters which can make flux to go from its maximum value in the positive direction to its maximum value in the negative direction and thus increasing the core utilization. So, one such converter is push-pull converter which we will see over here. This is nothing but our push-pull based DC-DC converter.

Now if you look in this particular push-pull converter we have in this instead of just using two winding here we are using four winding you know two on the primary side two on the secondary side and we are using the center tap to actually connect our different parts of the circuit. So here we have  $V_{in}$  voltage which is which is connected in this manner and we have D1 and D2 diodes which are connected on the other side in this particular manner. so let us see how this push-pull converter works here it uses four sets of winding and obviously they are all wounded on the same core and you can also make the center tap transformer as well on primary side it has two NP turns on the second side it has two NS number of turns and here again the S1 and S2 switch can be IGBT with freewheeling diode or MOSFET with body diode the diode represent the freewheeling diode or body diode if the switches are chosen as IGBT or MOSFET respectively so let us see how this particular push-pull converter operates now if we look very carefully in the first period where we have taken just  $\frac{DT_s}{2}$  period in this period which is you know yeah i mean if i take from here to here it is  $\frac{ts}{2}$  and if i take and this is another  $\frac{ts}{2}$  so overall this from here to here it is  $ts$  that means from this point to this point it is  $ts$  time period

Now, if you look very carefully in  $\frac{DT_s}{2}$  period, my S1 switch is on and my S2 switch is off and D1 of this side is on. So, that means this switch S1 is on. Now, this switch what we are using,

this switch S1 and S2 could be an IGBT and putting the freewheeling diode across the IGBT and or it could be a MOSFET which has body diode in that case we do not have to put extra diode already the diode will be there in the MOSFET. But for here in this case let us assume that switch a very generic switch s1 switch now which comprises of both the switch as well as diode if it is mosfet it will just be mosfet with bottle diode if it is with IGBT it is just the IGBT and we will connect the separate outside freewheeling diode now in  $\frac{DT_s}{2}$  period what happens is that this switch is on this switch is on means my this switch is turns this switches turns on now when this switches turns on what happens is that there is positive  $V_{in}$  voltage which will be applied across this winding and it has four windings. So, let us define this point A and B point. So, since here there is a positive  $V_{in}$  voltage applied across here because the switch is on. So, in this loop already this dot is connected to positive terminal  $V_{in}$  and non-dot is connected to the ground and that is when we will apply positive  $V_{in}$  from this winding. As a result of it since these all four windings are wounded on the same transformer core.

So, at that point, at the top winding also, we will have  $V_{in}$  voltage which get induced. On the secondary side, we have  $\frac{N_s}{N_p} * V_{in}$  voltage which get induced and in fourth winding, it is  $\frac{N_s}{N_p} * V_{in}$  voltage which get induced. Now because of this thing since we have positive potential applied over here this diode will get forward biased while this because the negative potential is applied to the anode of this diode this diode will get reversed bias and as a result of which we can say that D1 is on now since my D1 is on what happens is that the current in this one will start the because the positive potential is applied across the winding so current will start rising since the current is start rising what happens is that there will be current which will be coming over here and across  $v_L$  we have voltage applied nothing but  $\frac{N_s}{N_p}$  if we assume  $\frac{N_s}{N_p} = n$ . So, we can say it is  $(nV_{in} - V_o)$  voltage and this  $I_L$  which is going over through this one is coming and coming in this loop flowing in this particular loop

And that's when we will see the voltage across the inductor is  $v_L = (V_{in} - V_o)$ . And since our  $nV_{in} > V_o$ , we can say that in  $I_L$  current, the current which is going through this  $I_L$  current, there is a positive rise in, there is a positive slope which is nothing but you can say it is

$$I_L = \frac{(nV_{in} - V_o)}{L}$$

The slope is rising slope. And if you look the Since the positive potential is applied, which is  $V_{in}$  potential, so there is, let us say the flux starts from minus phi m value, there is a positive slope and that slope is nothing but, that means  $\frac{d\phi}{dt} = V_{in} N_p$  and it goes until it reaches up till  $\frac{DT_s}{2}$

period, it keeps on rising. And since D1 is the only which is conducting, so the current through D1 is nothing but equal to  $I_L$ , so this  $I_L$  will actually flowing through the D1.

And since my D2 is reversed bias, so the D2 current is actually 0. And since I have turned on my S1 switch, this voltage across this is 0. And the current which is coming over here will get reflected onto the primary side, onto this bottom winding. And that current is also flowing through this switch. We define  $I_{S1}$  to be like this.

It is 'n', it is nothing but  $nI_L$  current which is flowing through switch S1. And that is how our system will work in this way during first  $\frac{DT_s}{2}$  that means for half the switching period. Then comes the  $\left(1 - \frac{DT_s}{2}\right)$  period where what we will do is we will already my S2 switch was off. I will also turn off my S1 switch. That is when what you will see from the primary side there are no voltages which are been imposed onto the winding or which has been applied onto the winding.

What we will see is that whatever the current which is going through the inductor L, since this inductor L, the current has to find a pathway, so it will come from here, it will come from here. Since the windings are symmetrical, the current, this  $I_L$  current which was there will get distributed through  $I_{D1}$ , current through  $I_{D1}$ , and through  $I_{D2}$ . And in that case, both the D1, in order to ensure the current is going like this, both the D1 and D2 gets forward biased. And since they get forward biased, both the windings on the secondary side, top and bottom winding, both get short circuited. That's when we can say that  $V_{AB}$ , voltage is equal to 0.

Since my  $V_{AB}$ , voltage is equal to 0 here. Since my  $V_{AB}$ , voltage is equals to 0, so  $\frac{d\phi}{dt}$  is nothing but sorry  $N \frac{d\phi}{dt}$  is nothing but equal to voltage applied and since voltage applied is 0, so we can  $\frac{d\phi}{dt} = 0$ . That's when we can say that there is no change in the flux during  $\left(1 - \frac{D}{2}\right)T_s$  period and whatever the value the flux was at, it will remain at that value. That's why we just make the straight line in the flux thing. Now,

Here, what happens is that this  $I_L$ , which is going over there, gets distributed between  $I_{D1}$  and  $I_{D2}$ . If we assume that the bottom part of the circuit and the top part of the circuit are actually symmetrical to each other, the current will actually get divided by half in both the diodes D1 and D2. That's why we see this is the diode; this is nothing but if we do here, which is  $I_L$  current, this

is nothing but  $\frac{I_L}{2}$  current, and here also it is nothing but  $\frac{I_L}{2}$  current in this period. If we see very carefully, since my S1 switch is off and there is no voltage which is applied from this winding, this entire  $V_{in}$  is coming across this switch, and that has to block the voltage  $V_{in}$ . Since there is no current flowing in the primary path, there is no current, which is zero current through the  $I_{S1}$ . So, in this period, since my inductor current goes from the top winding and bottom winding, this  $V_o$  voltage is actually appearing across this inductor. If you do the KVL in this loop, since these two are connected together, that's why if you do the KVL loop here, what we will get is  $v_L = -V_o$  because this minus terminal will connect across this point through this winding, and this will already be connected here. So, the voltage across the inductor is  $v_L = -V_o$  if we do the KVL in this loop.

So, that is why we get the voltage  $-V_o$  applied, and because we have a negative voltage applied over here. So, here we will have  $-\frac{V_o}{L}$  through which the current is falling. And that is how we will get our entire operation of the circuit during the  $(1 - \frac{D}{2})T_s$  period. Now, in the next half of the cycle time, in the next  $\frac{T_s}{2}$  period, from here to here, we have reached the  $\frac{T_s}{2}$  period. Now, let us see in the next  $\frac{DT_s}{2}$  period, in the next  $\frac{DT_s}{2}$  period, what is the scenario?

In that scenario, since we have already seen what will happen when just S1 is on and when both S1 and S2 are off. Now, let us turn on the S2 switch. So, when you turn on the S2 switch, what happens is that across this winding, we are applying a negative minus  $V_{in}$  voltage. Because if this is on, S2 is on, in this loop, the voltage which is coming over here is nothing but this negative terminal V is connected to the dot end, and the positive is connected to the non-dot end. This was not the case in the previous  $\frac{DT_s}{2}$  period where our positive  $V_{in}$  was connected to the dot end, and the negative terminal of  $V_{in}$  was connected to the non-dot end.

Since that was the case here in bottom also the same voltage gets induced  $V_{in}$  voltage and on the secondary side we have dot will be negative which is we can say  $\frac{N_s}{N_p}V_{in}$  voltage will get applied. here again negative and positive  $\frac{N_s}{N_p}V_{in}$  voltage will get applied. Since the  $+\frac{N_s}{N_p}V_{in}$  which got induced is connected to the anode of D2 this diode D2 gets forward bias and since it is a  $-\frac{N_s}{N_p}V_{in}$  which is connected to the anode this will get negative potential so that's why this will get reverse bias and because of this what happens is that The voltage which is coming across the L is nothing but my on one side it is

$$\frac{N_s}{N_p} = (nV_{in} - V_o)$$

You can just do KVL in this loop. In this loop you can do minus this voltage

$$-\frac{N_s}{N_p}(V_{in} + V_o) = 0$$

and that will actually when you equal to 0 and that when you rearrange you will get this value.

Now, at that point, the  $I_L$  current which was there, since we know that our  $nV_{in} > V_o$ , so we know that we have a positive slope which is shown over here, which is nothing but  $\left(\frac{nV_{in} - V_o}{L}\right)$ . And if you look very carefully, since we are applying a negative potential across this winding, so the flux in the core will actually falls down with a slope nothing but  $-\frac{V_{in}}{N_p}$ . Slope, it will fall down. until the second  $\frac{DT_s}{2}$  period gets over and during that point my  $I_{D1}$  is 0 the current whatever  $I_L$  current is there will be flowing through the  $I_{D2}$  that is why  $I_L$  current is there and since my S1 switch is off so in this entire loop if you do this one.

so, we will get  $V_{S1} = 2V_{in}$  voltage which will be coming across the switch and that's what we will see that we have this  $2V_{in}$  potential coming over here across the  $V_{S2}$ . So that means  $V_{S2}$  has to be sized for  $2V_{in}$  potential and the S1 is not connecting the  $I_{S1} = 0$ . Then comes the next state where we will have next  $\left(1 - \frac{D}{2}\right)T_s$ .

This period where our S1 and S2 both are off and this IL current was in this direction and this is  $v_L$  voltage. The current of  $I_L$  is going like this. And since it is the same thing which we have seen in previous  $\left(1 - \frac{D}{2}\right)T_s$ , the current which is coming will get distributed in top winding and in the bottom winding. and because of that both the diodes get forward bias because this current this current has to find a pathway and that they will find a pathway only through this two path only and if we assume that this part of the circuit and this part of the circuit is symmetrical to each other then we can say that we our  $I_{D1} + I_{D2} = I_L$  and we can see if we assume these two are symmetrical we can say  $I_{D1} = I_{D2} = I_L/2$ . Now in this period what happens is that, again if you see the  $V_{ab}$  voltage,  $V_{ab} = 0$ .

Since  $V_{ab} = 0$ ,  $\frac{d\Phi}{dt} = 0$ . That's why we have the constant minus  $\Phi_m$  flux which is being applied in the  $\left(1 - \frac{D}{2}\right)T_s$  period. And since here in this loop, if you apply KVL in this loop, across the  $v_L$ , we have voltage minus  $V_o$  which is appearing. So, that's why here it will fall down with a slope of  $-\frac{V_o}{L}$ . And since  $I_{DL1}$  and  $I_{DL2}$  have equal current flowing, the  $I_L$  is getting

distributed among  $I_{DL1}$  and  $I_{DL2}$ . That's why here it is  $\frac{I_L}{2}$ , here it is  $\frac{I_L}{2}$ , and that's why we see that the average value of this is nothing but  $\frac{I_o}{2}$ , and the average value of this is nothing but  $I_o$ , where  $I_o$  is the current which is going into the load. The ripple will be going through the capacitor while the average value will be flowing through the load, which is  $I_o$ . And during that time, if you look very carefully, our  $V_{S1}$  will be nothing but since this is zero voltage. So, in this loop, if you analyze it, this  $V_{in}$  is coming across this S1, that's why it is actually blocking the S1 potential. And since the  $V_s$ , there is no current going through the S1 switch, which is zero.

Here, our  $V_{S1}$  is equal to  $V_{in}$ . So, we have seen in all the 4-period operation what we see is that when we do the volt-second balance of volt-second balance of of L. Now what we realize is we are actually applying  $-V_o \frac{DT_s}{2}$  period, and then it is falling. The current will be falling down, so that means the flux has to fall to the same value in  $\frac{DT_s}{2}$  period. So, in the remaining next period, it is in  $(1 - \frac{D}{2})T_s$  period. And these two values have to be zero; then only the current will go back to the same value. Otherwise, it will not return to the same value. The  $I_L$  current is like this, so the ripple part will be going through the capacitor while the while the constant  $I_o$  current, which is the average value of this, will be going through the load. This average value will only change if my load resistance changes. In this, the  $I_L$  current goes from minimum value to maximum value and then comes back to the same minimum value in  $\frac{T_s}{2}$  period, and thus it repeats itself in  $\frac{T_s}{2}$  period. So, we need to do the volt-second balance in  $\frac{T_s}{2}$  period.

So, when we do this calculation, we will finally get

$$V_o = nV_{in}$$

Same as what we got in the forward converter. Now, if you look at the operation of this particular converter, there are two things which are quite different from the forward converter. Two things are: the flux here is now going from  $+\phi_m$  to  $-\phi_m$ . That means the flux density is going from  $+B_{max}$  to  $-B_{max}$ . That is why we can, you know, if we do the,

$$V = \Delta B A_c f$$

if we do that, this  $\Delta B$  is going from  $+ B_{max}$  to  $- B_{max}$  value, and that's when we will get AC to be nothing but equal to the area of the core will be nothing but  $\frac{V}{2}$  and  $B_{max} f$ , which was not the case in the previous condition where we were having  $\frac{V}{N} B_{max} f$  because, previously, the flux swing was from 0 to  $\phi_m$ , but here the flux swing is from  $+ \phi_m$  to  $- \phi_m$ .

So, our core is fully utilized in this case, we can say. So that is the advantage we get. So, we can say that the advantage of this converter is nothing but the core is fully utilized. That means you have sized the core and you are using the full core. And here, if you look very carefully, if you see in the L The current going through the L, we have a current which has the frequency nothing but  $\frac{T_s}{2}$ . So, this inductor will see the current which is having  $2f_s$  of this converter.

That's when we have to filter out that twice the switching frequency component of the  $I_L$  current. That means the L and C have to be designed for twice the switching frequency, which was not the case in the forward converter. where we have to size our L and C for the entire  $T_s$  period. If you recall our, if you just recall our forward converter, we see our forward converter operation. Here, we see here, this one is for the entire  $T_s$  duration, the ripple is there.

So, L has to be sized for for the entire  $T_s$  duration that means for the L and C has to be sized for a cutoff frequency of same as switching frequency. However, in case of push-pull converter we have understood that the inductor current has twice the switching frequency current and that is when What we can say is that the cutoff frequency, we have to filter out that twice the switching frequency component of current in  $T_s$ . So, the cutoff frequency or you can say the frequency for which  $LNC = 2f_{sw}$ .

Those are the advantages. However, there are certain disadvantages. Now, the disadvantage is obviously the first point is the switch rating the S1 and S2 ratings are doubled that means they have to be sized for two times  $V_{in}$  voltage if you can see here the voltage applied maximum voltage applied in one  $T_s$  duration is nothing but two times  $V_{in}$ . So, it has to block twice the voltage rating and then the second thing which will which which can occur because of the uneven voltage drop across these switches when they are conducting there is a possibility of flux walking that means the flux which has to come back to the same point it will not exactly come

back to the same point here we have written  $V_{in}$ . So, it will not be  $V$  just it is  $V = (V_{in} - \text{the voltage drop across this switch } S1)$ .

When the  $S1$  is on so that is the  $(V_{in} - S1)$  switch here and here it is  $V = (V_{in} - \text{the voltage drop across this switch } S2)$  at this place so here it is actually  $\frac{(V_{in} - V_{S1})}{N_p}$  the non-adjusted the actual switches have some drop and here it is our  $\frac{(-V_{in} + V_{S1})}{N_p}$  and this  $V_{S1}$  and  $V_{S2}$  during when they are on switches are on are are having different voltages due to the different manufacturing processes or different devices and whenever they do production it will always be having different values because of that thing there there are unequal voltages which will be coming across this winding and that's when we our this slope and this flow will not be same and that's when we can say that there is some flux which will remain be there and which will actually have something like this will happen. So it is goes from here goes here goes there like this in actual case it should be like this but in real case it will be let's say if it starts from the same point it goes here and it will come back it will come back with a different slope so it reaches here then it will come back here it goes with the same slope here goes up here and then it will come up with different slope until this point and then here it is and then so it is going in one direction so the flux if we draw the flux with respect to time it is going in one direction and after some time this flux will keep on going going going and it will reach to the saturation value of the flux and that's when the core gets saturated and that's when it will cease to perform or it will stop performing as a transformer and i mean if you see in this way because of our

See, we have to come back to the same point, but it is not always coming back to the same point. It will have some DC shift which keeps on going, going, going. And after some time, this will reach the  $B_{max}$  value. This flux will reach the value corresponding to  $B_{max}$ . And that's when our core will get saturated.

So, the flux walking phenomenon. Phenomenon. which leads to core saturation after some time. So, you have to apply a certain method by which you can avoid this core saturation. One way is you can sense the transformer current or this current sense. You can sense this current and accordingly slightly change the duty ratio to balance out that flux walking. And the third thing, if you look very carefully, every coil has its own leakage inductance. That leakage inductance, let's say when switch  $S2$  was conducting, there was current going through this. Suddenly, in this case, when switch  $S2$  is opened, there is some negative potential which will come across here, which is nothing but  $L_{lk} \frac{di}{dt}$  in the negative direction. The reason it is in the negative direction is—sorry, the potential—the current was flowing in this direction through  $L_{lk}$ . Since you

suddenly switch this off, what we will get is a negative potential because my  $\frac{di}{dt}$  is negative, as the current goes from non-zero to zero value. So that's why our  $L_{lk} \frac{di}{dt}$  becomes negative, and that will come across this switch. By adding this  $V_{in} + L_{lk} \frac{di}{dt}$ , it will come across the switch, and the switch has to be sized for that voltage kick. That's why your switch has to be sized for that particular voltage. So, when we turn off, you will see that the switch will see the voltage something like this, which is  $L_{lk} \frac{di}{dt}$ .

When it goes from on to off. At that point, here we are drawn for  $V_{S1}$ . Similarly, for  $V_{S2}$ , it will also be the same thing. Now, this is one of the disadvantages. We can write the disadvantage as the voltage kick—or why we say 'kick' because it's applied for a very small period of time—so voltage kick due to the sudden breaking of current through leakage inductance. And this leakage inductance, this voltage kick, will appear on  $V_{S1}$  and  $V_{S2}$ . Voltage kick, you can say, on S1 and S2 switch. So, this has to be taken care of while designing this converter. Another disadvantage is that the four-winding transformer is or needs to be wound.

This is another disadvantage. So many, you know, windings of the transformer design will become quite complicated. So, we have seen the operation of, you know, this push-pull converter in this lecture. We will continue our discussion on going ahead with different converters, like full bridge and all, in the next lecture. Thank you.