CHARGING INFRASTRUCTURE

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Week-07

Lecture-33

Lec 33: Switching Loss

Hello everyone today we will be discussing the lecture number 33 of the NPTEL lecture series on charging infrastructure and this lecture since we have been revisiting our isolated DC-DC converter now one important thing which we must understand is about the switching losses and how those that losses occurs that we will discuss in this lecture because that will actually form the base For the next stages of discussion of isolated DC-DC converter, specifically the full bridge converter, the PWM strategies and another kind of modulation which is phase shift based modulation. So that's why in today's lecture we will discuss about the switching losses and on what factor the switching losses depends and because this will help us to understand the concepts for future lectures. So that's let us discuss that.

Now before starting that let us recap what we have discussed as of now we have discussed some of the isolated DC-DC converters and in all most of these isolated DC-DC converter what we have DC which is actually getting converted to high frequency voltages and that will be actually applied across on the secondary winding and accordingly we will then do the rectification and then we will get the output dc so in this thing we have revisiting some of the converters like we have visited forward converter again different configuration of forward converter we studied forward converter with demagnetizing winding dual switch forward converter then we have seen push-pull converter and after that we have in the last lecture we have discussed on the full bridge converter full bridge converter and half bridge converter also we have seen. Now mostly for high power applications generally people prefer full bridge converter operation primarily because it the core is fully utilized and also the voltage ratings of these devices are actually just the input voltage and also with this kind of converters we can also achieve the you know reduce loss operations as well we will discuss that in subsequent slides. So, we will discuss more in detail on this pole bridge converter as we go along in subsequent lectures. So, before starting that we have seen that we are converting the dc into the high frequency ac and that will be applied across the one of the transformer winding and accordingly voltage gets induced on the secondary windings and then it will get rectified and applied to the load. Now in this one we have seen that the why we went for configuration something like this where the transformer sees the high frequency excitation it's because with increase in frequency the requirement of the cross-sectional area of the core is less and that's when we can reduce the size and weight of our entire power converter. So that is one of the important factor so we are actually going from the dc to high frequency ac and that ac is applied across the transformer winding and since we would like to have smaller and lighter power converter because that's one of the requirement since these converters are most of the times are either put on the charger or on the vehicle in the form of onboard charger so we must ensure that the converter should be lightweight and smaller in size and one way to achieve that is to go for high switching frequency. And also, since we are going for a high switching frequency, we have corresponding switching losses in the switches and that we will evaluate or that we will see how those switching losses depend in this particular lecture. So, we have seen some of the operation of full bridge converter in the last lecture.

Now, let us start our discussion related to the switching loss. because we have seen that if we increase our switching frequency f_{sw} if we are increasing our cross section area requirement of the core gets reduced also the inductor and capacitor sizes are actually inversely proportional to switching frequency and that's when we can also get smaller smaller inductor and capacitance i mean inductor and capacitor i am talking about filter capacitor and inductor these are all filter components, i mean which was placed at the output of this converter. It's purely because we know that our cross-sectional area is

$$A_C = \frac{V}{N\Delta B f_{sw}}.$$

So, for the constant voltage number of turns and the maximum ΔB, our Ac or the cross-sectional area of the core is inversely proportional to the switching frequency.

And the other thing, if you recall our inductance value, what we have got?

$$L = \frac{nV_{in}D(1-D)}{2f_{sw}\Delta i_L}$$

If you recall our last class discussion, we got this inductance value. Similarly, our capacitance value, obviously, we are writing here for full bridge converter.

So, this capacitance value what we got was, we got our capacitance value to be

$$C = \frac{\Delta i_L}{8(2f_{sw})\Delta v_o}$$

we got this particular capacitance value this, so this is the inductance value and capacitance value obviously this is for full bridge converter and in both the things we see that the inductance and capacitance value is inversely proportional to f_{sw} frequency that means if i increase the f_{sw} frequency my size of a inductor and capacitor is less further if you look any dc dc converter i mean whether it could be our buck converter buck boost converter or our boost converter or isolated converters in all the converters. What we have we have some set of switches maybe 2 or maybe 4 depending upon the kind of converter we have then we have filter inductance, filter capacitance and if it is isolated DC-DC converter, we have the isolation transformer. And in all the things, if we look very carefully, the switches, the size of the switches and auxiliary circuit for those switches are not too much as compared to the size of, you know, our L inductance, capacitance and high frequency transformer.

So, the size of power converter is directly proportional to the LC and high frequency transformer and this these all this LC and high frequency you can say that these are passives you can say these are passives because they don't have any active component involved in that so the size of power converter is directly proportional to the size of passives and the size of passives is inversely proportional to the f_{sw} frequency so if we increase our f_{sw} frequency size of passives goes down size of passive goes down and if our size of passive goes down our size of power converter size and weight in both size and size we are talking in terms of volume as well as weight size and weight of power converter also goes down, that means our prime objective is to go for higher switching frequency that's when we can reduce the size of passes and that's when we can reduce the size of power converter.

However when we go for high switching frequency we have the switching losses which will be occurring in the switches. Now let us try to understand what will be the switching losses I mean how we can evaluate switching losses and in what factor the switching losses depends. So, let us take for calculating switching loss. Let us take simple buck converter. So, if we take a simple buck converter what we have is we have switches and the diode so this is a S1 switch and this is a diode D and let us take the output to be an inductor and a capacitor and the resistance R_L This is V_{in}, this is V_o we have.

Now, if you look very carefully this particular bridge the connection of i mean the switch and the diode you can also get the same thing by just having another switch instead of diode we could have the synchronous rectification where we remove this diode and connect another switch and whenever my S1 switch is off i will turn on my S2 switch or vice versa and whenever my S2 switch is on i will turn off my S1 switch both will have the same kind of operation So, to understand our, to have the basic understanding, if we see, we could have also achieved this thing by my S1 switch, my S2 switch with, you know, a freewheeling diode or you can say a body diode if I am using a MOSFET and this capacitance and then we have the resistance R_L and output V_o, output V_o. And both the things what we will see is we have this particular converter, this particular half bridge which is one of the conventional or you can say one of the building block of any voltage source converter. So, we can then and since we have this LC and this LC at the output of this switch and diode connection.

So, here what we will see is that if you see the I_L current, what we have is$I_L$current will consist of I_L current will consider nothing but average value which is nothing but going to I_o current going to the load I_o and it will have some ripple to it and let us assume this ripple delta I_L to be very very small if we assume this inductance value is very very large then we can say that the output of this combination of S1 and D is nothing but It's the constant current coming out of this or you can say the constant current, I mean current with a small, you know, this variation and small ripple. So, we can then take a circuit which is nothing but, circuit looks like, something like a constant current coming out of this and this is nothing but D this is S1 this is $V_{in}$and this is I_o current going on that I_o current we have a small ripple but we can assume that this ripple to be very small so we can assume this circuit. Now let us see how our losses in the switch S1 looks like so let us try to understand the scenario where what we have is we have circuit this is V_{in} voltage which is been applied and if we see that, so in this particular circuit if we see let us try to draw V_{in} the voltage V_{S1} and let us assume the current which is going through the V_{S1} is I_{S1} the current which is going through the switch is nothing but I_{S1}. And we can say that whenever my S1 is on, the I_{S1} is nothing but equal to I_o. And whenever my switch is off, the I_o will be circulating, freewheeling from this diode D. So let us try to make our understanding because if you look very carefully this is most of the time we can you know have the bottom synchronous rectification that means switch along with this freewheeling diode. So it is like a conventional you can say the half bridge.

So let us try to find out the losses in the switch S1. Let us make the switch goes from here it was off it goes to let us say on. and then maybe after some time it's get on here and that it is off here this is gate pulse of S1 now since we have gate pulse of S1 look like this so at that point since my switch turns on what happens is there the current through the switch will start you know will start rising So, if I write i_{S1}, so it will start rising. I am just trying to, you know, zoom out the instant.

So, this start rises and it reaches to I_o value. And till that point, till the point my i_{S1} is not equal to I_o, the remaining portion, because see, if you look very carefully in this circuit, there is current which is coming through the i_{S1} and in the other possible way, there could be some current going through i_d, through the diode. So, I_o is nothing but equal to i_{S1} plus i_d in this particular kind of half bridge we take. So, in this thing, what we see is that the is

$$I_o = i_{S1} + i_d$$

and if you look very carefully in this thing since my $i_{S1} \neq I_o$ there will be some diode current which is going through it and that's when the voltage across this diode is nearly 0 and that's when since the voltage across the diode is nearly zero. The voltage across the switch S1 is still holding this V_{in} voltage because previous to that it was having the voltage V_{in} if we DV_{S1}. Since it was off It was off, it was on. So the entire voltage will be appearing across this S1 switch. So we were having the voltage V_{in} and then the moment at at this time you have given the signal to turn on this S1 switch the current is slowly start rising through the S1 switch and then some portion is coming from this channel while the other portion of the output current is coming from the diode and because it is coming from the diode diode is forward biased and since it is forward biased, so this voltage is still this point voltage is still hold to zero volt if we take with respect to ‘n’ it is still hold to zero volt and that's when the entire dc link or entire V is actually coming across the switch S1. So, the switch will still be having voltage S1 and then after some time whenever the current reaches to I_o value at that point the diode gets reversed bias and that's when the voltage which was here will now then fall to 0, because if it is get reversed bias this voltage will start appearing across the diode. So, what we see is that the voltage will fall down and become 0. Now here we assume some considerations that switches when it is off it is i mean it is having zero voltage and when it was not conducting the current through this which is actually zero So, that is some consideration and we have also not considered any forward voltage of the diode and the effect of non-linear input and output capacitance of devices for our easy calculations. So now there is a time when their current is rising, so let us say this time to be t_{ri} the rising of the current and there is a time during which my voltage is falling, let us say this time to be falling of the voltage t_{vf} and and then we can say that T_{SW} switch on the T_{SW} on the time for turning on the switch is $t_{sw(on)} = t_{ri} + t_{vf}$, and if we see this particular system if we try to find out the losses which is happening through the switches ,so let us first try to i mean just let's try to find when $0 < t < t_b$, that means from this point to this point if we assume this to be $t = 0$, then we can say that i_{S1} which is also varying with time ‘t’, if it is all these are varying with time t, so this is a rising thing. so, we can write this is to be

$$i_{S1}(t) = \frac{I_o}{t_{ri}}.t$$

Similarly, we can write Vs1 of T,

$$v_{S1}(t) = V_{in}$$

the voltage across this one is to be nothing but equal to V_{in} voltage. And that's when we can now evaluate our energy loss during t_{ri} period, energy loss during t_{ri} period that means during the rise time of current the $T_s = \frac{1}{f_{sw}}$. So, what you can say if it is off over here and let us take some time that after off after some time it gets on here again so from here to here we have T_s period and we can also say that during when it is turned off

When the switch gets turned off, what happens is that we have first the voltage which just rises up. When it is turning off, it is vice versa which will happen where the voltage will first rise to V_{in} voltage and when it rises to V_{out}, V_{in} voltage then only the diode will get forward bias otherwise if it is not V_{in} then there is some positive voltage which will be appearing across cathode to anode or you can say the cathode will be at higher voltage as compared to anode that's when it was reverse bias so during this time it reaches to V_{in} and then only your current till that point your current will be with the i_{S1} and then after that only it will goes down to 0 and that is when here the current will be flowing through the i_{D1} at this place so i mean through the diode so that is why we can say this point we have you know . So in the switching cycle if we see turn on is happening once in a switching cycle that's why we are taking the average energy loss during the ts duration in for the in the t_{ri} region So, let us try to find out the energy loss during t_{ri} period.

So, it is E TRI we can write

$$E_{t_{ri}} = \int_0^{t_{ri}} i_{S1}(t) v_{S1}(t)\, dt$$

$$E_{t_{ri}} = \int_0^{t_{ri}} \frac{I_o}{t_{ri}}.\, tV_{in}\, dt$$

$$E_{t_{ri}} = \frac{V_{in} I_o}{t_{ri}} \int_0^{t_{ri}} t\, dt$$

$$E_{t_{ri}} = \frac{V_{in}I_o}{t_{ri}}\frac{t_{ri}^2}{2}$$

$$E_{t_{ri}} = \frac{V_{in}I_o}{2}t_{ri} \quad (1)$$

so what we have done we have calculated the energy loss only the energy loss during the TRI period and then let us calculate the energy loss during t_{fv} period let us take when the time is going between $0 < t < t_{fv}$ period that means during this period of time during this period of time from here to here now if we look there so we can write

$$i_{S1}(t) = I_o$$

$$v_{S1}(t) = V_{in} - \frac{V_{in}.t}{t_{fv}}$$

So, then we can then calculate energy loss during t_{fv} period. Now, when we do the calculation, we will get

$$E_{t_{fv}} = \int_0^{t_{fv}} I_o\left(V_{in} - \frac{V_{in}.t}{t_{fv}}\right)dt$$

$$E_{t_{fv}} = I_oV_{in}\int_0^{t_{fv}}\left(1 - \frac{t}{t_{fv}}\right)dt$$

$$E_{t_{fv}} = I_oV_{in}\int_0^{t_{fv}} 1.dt - \int_0^{t_{fv}}\frac{t}{t_{fv}}dt$$

$$E_{t_{fv}} = I_oV_{in}\left[t_{fv} - \frac{t_{fv}}{2}\right]$$

$$E_{t_{fv}} = \frac{V_{in}I_o}{2}t_{fv} \quad (2)$$

Now we know that what is the energy loss during this t_{ri} period and what is the energy loss during this t_{fv} period.

So, then we can now calculate the energy loss during the $t_{S,ON}$ period because this total is nothing but $t_{Sw,ON}$. If we see from the previous slide, it is nothing but $t_{S,ON}$. So, this period is nothing but $t_{Sw,ON}$. So, let us take the energy loss during the $t_{Sw,ON}$period. So the energy loss during the $t_{Sw,ON}$ period, so we can write it to be

$$E_{on} = E_{tri} + E_{tfv}$$

$$E_{on} = \frac{V_{in} I_o}{2}(t_{ri} + t_{fv}) \quad \text{(from eq (1) \&(2))}$$

and this is energy during turn-on: that means the time during which these switches, the transition of voltage and current looks like.

$$E_{on} = \frac{V_{in} I_o}{2} t_{Sw,ON}$$

Now, since we have calculated our $P_{Sw,ON}$, and if we look very carefully in one sampling period or in one switching period, Ts period, our switch turns on and then it turns on in the next switching period only. So, we can say that the power loss during switching on is nothing but, you can say

$$P_{Sw,ON} = \frac{V_{in} I_o}{2} \frac{t_{Sw,ON}}{T_S} \quad (3)$$

Now, this is let us define this as equation number 3 because this is the power loss during switch ON.

And we can also then see what is the power loss during switch-off. So, when it is switched off, we have understood that it was first I_o was remaining at this point and voltage is rising, so here we can just write this to be t_{rv} and this time period to be t, since current is falling t_{fi}, and if we do this entire thing is nothing but t switch-off. So during switching off or during turning off, you can say when the device is going to turn off So that time, you know, when $0 < t < t_{rv}$, what we have is

$$i_{S1}(t) = I_o$$

$$v_{S1}(t) = \frac{V_{in} \cdot t}{t_{rv}}$$

Now, if you try to calculate energy loss during t_{rv}, we will get $E_{t_{rv}}$ is

$$E_{t_{rv}} = \int_0^{t_{rv}} i_{S1}(t) v_{S1}(t)\, dt$$

$$E_{t_{rv}} = \int_0^{t_{rv}} I_o \left(\frac{V_{in}.tI_o}{t_{rv}} \right) dt$$

$$E_{t_{rv}} = \frac{I_o V_{in}}{t_{rv}} \frac{t^2}{2} \Big]_0^{t_{rv}}$$

$$E_{t_{rv}} = \frac{V_{in} I_o}{2} t_{rv}$$

So, let us take the switching energy energy loss during t_{fi}, so when $0 < t < t_{fi}$ we can write

$$i_{S1}(t) = I_o - \frac{I_o.t}{t_{fi}}$$

$$v_{S1}(t) = V_{in}$$

So, that's when energy loss during t_{fi} period is.

$$E_{t_{fi}} = \int_0^{t_{fi}} i_{S1}(t) v_{S1}(t)\, dt$$

$$E_{t_{fi}} = \int_0^{t_{fi}} I_o - \frac{I_o.t}{t_{fi}}.V_{in} dt$$

$$E_{t_{fi}} = I_o V_{in} \int_0^{t_{fi}} 1.\, dt - \int_{01}^{t_{fi}} \frac{1}{t_{fi}}\, dt$$

$$E_{t_{fi}} = I_o V_{in} \left[t_{fi} - \frac{t_{fi}}{2} \right]$$

$$E_{t_{fi}} = \frac{V_{in} I_o}{2} t_{fi} \qquad (4)$$

Now, this is let us define this as equation number (4). So we can say energy loss during turn off case is

$$E_{sw(off)} = E_{trv} + E_{tfi}$$

$$E_{sw(off)} = \frac{V_{in} I_o}{2} (t_{rv} + t_{fi})$$

$$E_{sw(off)} = \frac{V_{in} I_o}{2} t_{sw(off)}$$

and then we can say the power loss during turn off or turn off power losses we can say that and this power loss is happening once in a switching period because on it turns off only once in a switching period so we can just reveal

$$power\ loss\ during\ turn\ off\ = \frac{V_{in} I_o}{2} t_{sw(off)}$$

(5)

and just like we got it in the case of during the turn on case that we will define as an eq. no 5.

Now this one this value you will get it from equation three and four now we calculated the power loss during turn off case similarly we have calculated the power loss during switching on or turn on case. So let us try to see the overall switching losses in the power converter so we can say the power loss during switching. That means during turn on and turn off is P switching or switching power loss

$$P_{sw} = P_{sw(on)} + P_{sw(off)}$$

$$P_{sw} = \frac{V_{in} I_o}{2} (t_{sw(on)} + t_{sw(off)}) f_{sw}$$

That means the time during which while going for turn on the current rises from 0 to I_o and voltage falls from V_{in} to V_0 that time plus the time during which during turn off case the voltage goes from 0 to V_{in} and then the current falls from I_o to 0 that summation of that particular time multiplied by f_{sw} and and if you look very carefully if you try to see, how the loss varies. So from if you take in this period this multiplication of this we are seeing that it is going up it reaches to maximum value and then here it is right it is falling it is this one it goes down and becomes zero so this is nothing but your you can see piece which is in p or the power loss power loss similarly in this time here it is rising and this is constant this is rising and this is falling over this entire period so this is the nothing but the power loss during turn on switching on case or turn on case and power loss during turn off case switching off case now this particular term if you look very carefully the switching loss across the devices because we have consider our converter to be you know we have this s1 switch and the diode and we have a current output current from this you know kind of a bridge half bridge where we assume that the bottom the switch is not in picture we have only freewheeling diode or body diode of the MOSFET which is being connected at the second switch or S2 switch in place of S2 switch we have just considered the diode D so during this period we have understood that the switching loss which is happening across the device S1.

Obviously, we have calculated for S1, the switching loss for S1. Similarly, we can do it for, you know, if we have, let us say, two devices, S1 and S2. So, similarly, we can do it for S2 as well. So, however, what we understood that the switching loss depends on first switching frequency that means if you keep your switching frequency higher your switching losses will be higher because power loss is directly proportional to $f_{s\omega}$ and we can see also one more thing that is in in case of isolated bcc converter we are going for high switching frequency to reduce the size of the passives that means transformer and inductor and capacitor. We are actually incurring more and more losses because we are having so many switchings so many times the switches get switch on and off that's when we have so many occurrence of those loss of energies and that's when we have higher switching loss so depends on switching frequency it depends on the blocking voltage that means when it is off the amount of voltage it is blocking and when it is you know when it is turning on amount of voltage has to fall down and when it is turning off the amount of voltage which is needed to must be built across it so that depends upon that blocking voltage then it depends on the current during switching instant. So you can say switching current or the current which it has to go to when it turns on and the current when it is turned off the amount of current it has to go from non-zero value to zero value that is the current so that means the current during the switching instance here it was we have assumed that this current is constant I_o so here it is I_o if it is having a ripple then accordingly that ripple component also has to be added into the current. because you know when it is turning on. So that time my current through the inductor will actually be rising up because we are applying the positive voltage across the inductor and when whenever it is turning off we are applying the minus v naught across the inductor that's when we have falling current so during turn on instance we have to take the current from you know $I_0 - \frac{\Delta i_L}{2}$and while it is turning off it has to be $I_0 + \frac{\Delta i_L}{2}$.

So that ripple has to be considered when you are taking the exact calculation. However, roughly, if the ripple is very small compared to the average value, we can neglect that. And finally, we have the turning on and turning off period. Turning on and turning off time, or you can say period, means the turning on and turning off time corresponds to turning on. We can write the time required for turning on and turning off, so it depends upon that as well. So, if we want to reduce the switching loss—let's say if you are going for a higher switching frequency—you cannot reduce the switching frequency. The other things you can reduce are the voltage blocking across the switch or the current being carried during the switching state. For example, let's say when the switch is turning on from off to on, if I can somehow ensure before the turning-on instant that the voltage across the device goes down to zero, I can get zero switching loss. And while turning off, if I can somehow ensure before the current goes from a non-zero value to zero, if I can ensure the current goes to zero, I can ensure the switching loss is very small or you can say zero. So this is what we will discuss in the next lecture. In this lecture, we have understood the factors on which the switching losses in the switches depend, and the same thing we can apply. Let's say if your system has six switches or four switches, you have to calculate the switching loss across each switch in the same manner as we have derived. We will get the same formula and can use it to derive the switching losses. And that's how we can calculate the overall switching losses in a power converter. We will discuss more about this. I mean, what understanding we got from this and how we can apply it to short switching scenarios.

We will see this in the next class. Thank you for your patience and attention to this lecture.