CHARGING INFRASTRUCTURE

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Week-03

Lecture-12

Lec 12: Single-phase Boost PFC Converter - IV

Hello everyone welcome to this lecture number 12 of the NPTEL lecture series on charging infrastructure and in this lecture we will continue our discussion on single phase boost PFC converter so if we recap some of the things we have studied in the context of single phase boost PFC converter. So, what we have is we have studied that this boost PFC converter consists of a rectifier at its first stage then followed by a boost converter which has the input nothing but 'vd' where $v_d = |v_s|$ and then the switches S1 and S2 are switched at a high switching frequency in such a manner that on an average sense you can apply the variable V,converter voltage and that's when one can control the current which is coming out of the converter in such a manner that that this current will be following the same pattern as that of 'vd' and without having any phase difference. At the same time the disc switches need to also switch in such a manner that along with this current being in the same phase as that of the 'vd' or this current which is again you can say that it's a rectified version of the current drawn from the ac input. So, this is current and this 'vs' is in the unity power factor so this switch needs to operate in such a manner that this 'vs' and is is in the unity power factor as well as the output voltage is controlled within or is regulated within the permissible range of the voltages. So, for that we have understood that the duty ratio d(t)of this S1 switch which is nothing but the fraction of the time in the switching period when the switch S1 is on is nothing but 1 minus modulus of vs,pk sine w t divided by Vo.

$$d(t) = 1 - \frac{|v_{s,pk} \cdot sin(\omega t)|}{V_0}$$

The inductance we have again calculated the inductance value which is nothing but Vnaught divided by 4 multipled delta iL,max fs, where fs is the designer choice.

$$L = \frac{V_0}{\left(4 \cdot \Delta i_{L,max} \cdot fs\right)}$$

Generally, this 'fs' will be very very much greater than the line frequency or the input AC voltage frequency. and the delta iL,max is nothing but again it's the designer's choice or sometimes it is also given the specification that what could be the maximum ripple in the current one can expect or one can allow in the inductor current so that will be $\Delta Lmax$ that will actually will determine the value of this inductance and this V_0 is again can be derived from the specifications.

Similarly, the capacitance value,

$$C = \frac{P_L}{\left(2\pi fs.\Delta v_O.Vo\right)}$$

this capacitance value sees double line frequency double line frequency component on the output voltage or on its voltage that means you have the ripple on that capacitor which has the double line frequency component now this is one of the drawback of single phase boost PFC converter or in single phase ac to dc converter in general and this capacitor the capacitor need to be sized to actually limit that double line frequency component within the permissible limit and that requires a good amount of capacitance value and thus it is one of the bottleneck of single phase ac to dc converters. Again, those converters we are operating in such a manner that it is drawing unity power factor current and able to maintain the output voltage within a permissible voltage range. So, this double line frequency component on to the capacitor voltage is one of the drawbacks and it is one of the critical aspects, which actually determines the size of capacitance and that will actually determine the overall size of that single-phase AC to DC converter. And then we after understanding the value of 'L' and 'C' we have started seeing different ratings of the switches because one also has to select the appropriate switches. So, we have for that we are defining the rms current which is flowing through the switches and for that we have seen rms current flowing through the switches in a very generalized converter case where which has half bridge and having the current I naught coming out of that half bridge, I mean constant current I naught coming out of that half bridge.

So, that we have seen and when the assay is conducted for d fraction of time in a switching period, then we can write down that RMS current of that switch assay or the current which is flowing through switch assay 'irms,sa' nothing but I_o times under root of d.

$$I_{rms,Sa} = I_0\sqrt{D}$$

So, this we have derived from very generic voltage source converter which has this half bridge as a fundamental building block. And that particular expression or that particular understanding we have expanded it to this particular S1 switch and there we saw that I,S1 is nothing but under root 1 by T divided by 2. Again T is nothing but 1 divided by fs, which is a time period corresponds to the line frequency or the ac input frequency going from 0 to T divided by 2. Because this the average current which will be flowing through this inductor will repeat itself after T/2period or after half the cycle it will repeats because if we see the 'vd' will look like this And 'iL' or you can say 'iL' average or 'id' average will also look like this because we are making sure that converter is operating with a unity power factor current or the current drawn from the AC voltage source will have the same phase as that of the grid voltage.

$$I_{rms,S1}\sqrt{\frac{2}{T}\int_{0}^{T/2} i_s^2(t)(1 - d(t)]dt}$$

So here this is the average value of you can say id average or iL average. And the actual current will have something like ripple associated with that. So, the current will have the I mean you can say that double line frequency component you can say which is nothing but this is which repeats itself in $T/2$ period. So, that is why since the operation or the operation of circuit will repeat itself after every $T/2$ period. So, we have taken 1 divided by $T/2$ period going from 0 to $T/2$ 'is' square. So here whatever so whenever in the positive half cycle whenever this D1 and D4 is forward bias, your 'is', 'is' nothing but equal to id. So that's why the same is will be flowing through the 'id' and the same 'id' will be flowing through the switch S1. So, in every switching period the duty is changing that is when the RMS current flowing through the switch will be varying. So, that we have calculated for each cycle and we are taking the mean over the entire half line cycle. So, that is when it is 'is' square times dt or d (t) and variation I mean that is a summation going from 0 to $T/2$ So, that will give you the RMS current of the switch S1.

And then when whenever the switch S1 is off that means S2 is on so whenever the S2 is on this entire Vo is coming across this switch S1. So, we can say that the voltage rating of this has to be greater than Vo which is generally it is taken as between 40 to 60 percent and that is somewhere around one point. I mean if the with some safety margin one can select let us take 40 percent safety margin, so the voltage which voltage rating of I mean which will which you will be using to select the particular device should be at least 1.4 times $V_{S1} \geq 1.4 \cdot V_0$ that of the output voltage which will be there in the converter.

Now let us further see our discussion related to switch S2 so for switch S2, In. the same line of S1, we can see that this switch S2 conducts only during $(1 - d(t))Ts\ r$duration. That means if Ts is the switching period, so S2 conducts for this much time. And whenever the S2 is off, that means as whenever the S1 is on, then VS2 has to block the entire Vo. If you do in this particular KVL, if you do KVL in this particular loop, whenever the S1 is on, this entire Vo will be appearing across this S2 switch. So that's when VS2 has to block the Vo. Generally, we take some with some safety margin. So VS2 will also be 1.4 times of Vo. so that will you know generally you select the device for this S2 in such a manner that it should be in a position to block 1.4 times of Vo, $(V_{S1} \geq 1.4 \cdot V_0)$. And let us also calculate the rms current which will be flowing through this in the same manner as we have calculated for S1 switch so let us calculate irms for S2 switch.

Again, this S2 switch will the operation or the current will be flowing through the S2 switch will repeat itself after T/2period. So we will do T/2period and then the mean we will be taking for 0 to T/2period and in each switching cycle we are actually allow or we or the S2 is actually conducting only for (1-d(t)) fraction of the time of that switching cycle so our duty ratio of this S2 switch is nothing but (1-d(t)) and the current which will be flowing through this one 'is' during positive half cycle what we can see that the 'is' nothing but equal to 'id' and that same 'id' will be flowing through the S2 switch when whenever the S2 switch turns on and S1 is turns of S1 turns off. So, we can write down that it is this 'is' current which is going through the S2 switch 'is'(t) square times. The ratio of the time during which this S2 switch is on so which is nothing but (1-d(t)) fraction of the time. It is been conducting and then take the root mean square over the entire half line cycle going from0toT/2period.

$$I_{rms,S1} = \sqrt{\frac{1}{T/2}\int_0^{T/2} i_s^2(t)(1 - d(t))]dt}$$

It is because the operation of the boost converter which is the second stage repeats after every half cycle of the line frequency that means 50 or 60 hertz. So that is why we have taken 1/T/2 period. Now, this will define the RMS current. Again, this particular expression, one can put the value of d(t). And since we are assuming that the converter is operated with a unity power factor current, so we can write directly 1 / T/2, nothing but is,peak sine wt. (1 -d(t)) is nothing but (1 –(1-$\left|v_{s,pk} \cdot \sin sin\ (\omega t)\right|/Vo$)), that one can easily do okay when this is going to 0 to T/2 so we can write 0 to T/2 sine wt - sine wt by Vo and this has to be integrated over the half line cycle or half line cycle period. So, then you can calculate this irms which will be flowing through this current through the switch S2 and this you can easily put it in some advanced mathematical tools and try and you can easily find out the value of this integration this vs,peak you already know because once the specification is been given you know that what is the peak voltage your input can go so that you know because generally rms of input voltage has been given so you from there you can calculate to vs,peak and once the converter specification is given already the output voltage will already be defined so these two things are known ispeak you can easily calculate by doing or by under or by recalculating the power which will be which will be drawn from the grade from there since rms voltage value you already know so you can easily calculate the is,peak as well.

$$I_{rms,S2} = \sqrt{\frac{1}{T/2}\int_0^{T/2} \left(i_{s,pk} sinwt\right)^2\left(1 - \left(1 - \frac{\left|v_{s,pk}\cdot sin(\omega t)\right|}{V_0}\right)\right)]dt}$$

$$I_{rms,S2} = \sqrt{\frac{1}{T/2}\int_0^{T/2} \left(i_{s,pk} sinwt\right)^2\left(\frac{\left|v_{s,pk}\cdot sin(\omega t)\right|}{V_0}\right)]dt}$$

So, that is how one can easily calculate the current which will be flowing through the S2 switch one already know the voltage which will be appearing across the across the S2 switch already know what is the rms currently flowing through the S2 switch and thus one can easily select the required device which can be used in this converter on the similar line one can also calculate the average current which will be flowing through this switch S2 that also one can calculate and that will help the designer to select the appropriate switches. So, if you want to calculate I average going through S2 switch again we have to find the average.

So, it is again mean taken over T/2 period going from 0 to T/2 period. And here since you have to calculate the average current which will be flowing through this. So, you can easily do it by writing 1 minus d(t)P. So, in each cycle it will be this particular switch will be conducted for 1 minus d (t) fraction. So, this will be is times 1 – d(t) and that you have to take an average from 0 to T/2 and that's when by solving this particular expression again d(t) one can put an 'is'(t) which we assume that the current drawn from this source is nothing but having a unity power factor. So, this is nothing but is,peak sine wt having the same phase as that of the grid voltage.

$$I_{avg,S2} = \sqrt{\frac{1}{T/2}\int_{0}^{T/2} i_s(t)(1 - d(t))]dt}$$

So that's when you can put and you can easily calculate the average current through the switches too and accordingly one can select I mean if one has to select the IGBT so accordingly based on this current rating based on average current rating they can select the IGBT if someone has to select the MOSFET they can use the RMS current so that's how one can select the required switches in the boost PFC converter. Now let us try to evaluate how one can select what will be the diode rating one need to select. So, let me take for diodes. And again if you see if you look very carefully since this diode is having the same functionality as it was there in case of full bridge diode rectifier where D1 and D4 are forward biased during the positive half cycle and D2 and D3 will be forward biased during the positive half cycle negative half cycle so thus the concepts what we obtained or what we derived during the discussion of full bridge diode rectifier or uncontrolled rectifier the same concept will also look will also be following in here so you can write easily that the peak voltage which these devices has to block is nothing but VRRM is nothing but vs,pk because your vd is nothing but modulus of vs,pk sine wt .

$$v_{RRM} = v_{s,pk}\text{, because } v_d = |v_{s,pk} sin\omega t|$$

And then whenever the D1 is on that entire $|v_{s,pk} sin\omega t|$will be appearing across this D2. So, the diode and the same thing will be there in the negative half cycle for D1. So, the maximum rating for which the diode, I mean diode need to be sized will be nothing but vs,peak or the peak value of the input sine wave.

And similarly, one can calculate the forward RMS current. To do that, in one-line cycle, this D1 and D4 will be in conduction from 0 to T/2 period, while it is not in conduction from T/2period to T period. So, and then again the cycle repeats after one line cycle. So, we can just do the forward current nothing but under root 1 / T period going from 0 to T/2, because in T/2to T it will be conducting a zero current. Will be nothing but we can if we take is,peak sine wt is the current we assume that if this current is having the unity power factor so we can say that square is,pk sine wt of that duty. So that one can easily evaluate and they will get nothing but is,pk divided by 2 that is a forward rms current of this diode.

$$forward\ RMS\ current\ = \sqrt{\frac{1}{T}\int_{0}^{T/2} \left(i_{s,pk} sinwt\right)^{2}]dt}$$

$$= \frac{I_{s,pk}}{2}$$

So, that will be used to to actually select the diode having required it rating similarly one can calculate average or forward average current which will be nothing but again 1 / T going from 0 to T/2 is,pk sine wt dt and that if one solves it they will get is,peak by pi that will be average forward current going through the diode.

$$forward\ average\ current\ = \sqrt{\frac{1}{T}\int_{0}^{T/2} i_{s,pk} sinwt]dt}$$

$$= \frac{I_{s,pk}}{\pi}$$

And accordingly, diode can be diode rating can be selected. So, in this way one can select all the four diodes so we have seen up till now the switches rating diode rating the capacitance value inductance value. Now we have to calculate the rms current which will be going through this inductor and the rms current will be flowing through this capacitor. So, let us see in the maybe in this one end of capacitor and inductor, so let us first see for inductor so since the current flowing through the inductor $iL = i_d$, we can then and this 'id' is nothing but equal to 'is'($i_d = i_s$) in positive half cycle and it is equal to minus 'is' ($i_d = - i_s$) in negative half cycle. So, in magnitude wise this both this 'id' and 'is' are nearly same so what we can do is we can and since this 'is' same as 'is' so we can write down iL,rms.

And now if you see very carefully this 'iL' will be there I mean the current through the 'iL' will be always be there whether it is whether switch S1 is turned on or whether switch S2 is turned on and this 'iL' current will repeat itself after every half cycle or that means after every T/2period. It repeats itself so that's why we have taken 1 / (T/2) going from 0 to T/2square of is,of t dt dt plus 0 to T/2square of is,of t dt dt emission going up to dt so that if we do addition what will we get is 1 divided by T/2going from 0 to T/2is of t square into d(t)and if we consider that it is zero is of t is nothing but is peak sine w t where one can do and that will be nothing but is,peak by root 2 that is nothing but rms current of this inductor.

$$I_{L,rms} = \sqrt{\frac{1}{T/2}\int_{0}^{T/2} \left(i_s(t)\right)^2 (d(t)).dt]dt + \int_{0}^{T/2} \left(i_s(t)\right)^2 (1 - d(t)).dt}$$

$$I_{L,rms} = \sqrt{\frac{1}{T/2}\int_{0}^{T/2} \left(i_s(t)\right)^2 (d(t)).dt]}$$

$$I_{L,rms} = \sqrt{\frac{1}{T/2}\int_{0}^{T/2} \left(i_{s,pk} sin(\omega t)\right)^2 (d(t)).dt]}$$

$$I_{L,rms} = \frac{I_{spk}}{\sqrt{2}}$$

So accordingly depending upon this current because we already know is,peak how one can calculate is,peak. So generally, in the specification PL is already given so one from this PL one can calculate 'pin' is nothing but PL by efficiency of the converter we can assume one efficiency and then we can easily calculate how much amount of power need to be drawn from the input and we already know the 'pin' is nothing but vs,peak by root 2 and is,peak by root 2. And that we know that we can easily calculate our is.pk nothing but 2 multiply Pin divided by vs.pk.

$$P_{in} = \frac{P_L}{\eta}$$

$$P_{in} = \frac{I_{s,pk}}{\sqrt{2}} \cdot \frac{v_{s,pk}}{\sqrt{2}}$$

$$I_{s,pk} = \frac{2P_{in}}{v_{s,pk}}$$

That's when one can easily calculate is,peak and from that one can calculate what will be the RMS current flowing through the inductor and that will be useful for actually selecting the wire size of the inductor which will be bonded over the core to obtain the required inductor. So, similarly we can also calculate in the similar lines we can let us also calculate the RMS current flowing through the capacitor. So, we know that we know that for capacitor let us calculate rms current we know that the current which will be flowing out of this the half bridge of this boost converter is nothing but will be going to some portion will be going to ice to the capacitor another portion is going to the to the load.

So we can easily calculate this I converter. This I converter is nothing but the same as that of the current which will be flowing through the S2. So we can say that I,rms converter is nothing but—I mean, this RMS value of this current is nothing but—I'm sorry, we can change the notation. I,rms of converter is nothing but I,rms of S2, and we know that. I converter is nothing but 'ic' plus 'iL'. So the ripple part is going through the Ic, while the average value will be going through this load RL. So we can calculate Irms of C is nothing but. I,rms of converter squared minus iL squared.

$$I_{rms,conv} = I_{rms,S2}$$

$$I_{conv} = i_c + I_L$$

$$I_{rms,C} = \sqrt{\left(I_{rms,conv}\right)^2 - \left(I_L\right)^2}$$

and $I_{rms,conv}$ this particular thing is nothing but the same as I,rms of S2. And this we can easily calculate iL value is nothing but Vo / RL.

And thus we can calculate what is the RMS current flowing through this capacitor. We can come to the conclusion of what. Will be the current, and thus we can easily size the capacitor bank—that means a parallel combination of capacitor bank—one can decide. So till now, we have seen all the four diode ratings. We have seen all the switch ratings. We know what is the value of capacitance. We have also seen the RMS current flowing through the capacitance. We have seen the value of inductance. We have also seen the RMS current flowing through the inductor. And using this information, one can. Select the required component and can build this kind of power converter for the required specification, which includes some information like output voltage, input voltage, output power, permissible voltage ripple, and what is the AC frequency. Using those information, one can easily.

And following this procedure, one can easily size the component accordingly and thus can build the power converter of the single-phase boost PFC converter. Now, we will see in the next lecture how to control the functionality of this converter such that we get unity power factor current drawn from the source, and we could regulate or control the output voltage at a desired level or at the required level. Thank you for your patience in listening to this lecture. We will see you in the next lecture.