CHARGING INFRASTRUCTURE

Prof. Apurv Kumar Yadav

Department of Electrical Engineering

Indian Institute of Technology Roorkee

Week-04

Lecture-20

Lec 20: DCM operation of Boost PFC Converter

Hello everyone welcome to the lecture number 20 of this NPTEL lecture series on charging infrastructure and in this lecture we will study the DCM operation of boost based PFC converters in the previous some of the lectures we have studied the operation of boost PFC converter which consists of a diode bridge as the first stage, diode bridge rectifier as the first stage and then followed by a DC-DC boost converter after that. Now if you look very carefully in this particular thing we have also seen the derivative or the bridgeless PFC based where this is nothing but a bridgeless PFC which is again which does not have any diode with rectifier however it is also having the same kind of functionality which is having the kind of a boost converter system and here if you look very carefully if you look very carefully in both the things we are actually trying to control the current through the inductor this i_L here which is nothing but unfolder version i_S or you can say the modulus of i_S , i_S nothing but equal to i_L.

$$i_L = i_S = |i_S|$$

So, we are trying to control the current going through the inductor and that's when we could able to control the current which is been drawn from the source and we can ensure that unity power factor current is been drawn from the source by doing the closed loop control and in the closed loop control we have seen two things one obviously we have seen average current control where we kept our switching frequency of the devices S1 and S 2 and here again S1 and S 2 the switching frequency of the devices are kept constant and in the entire time at the entire time we have seen that the inductor current has some average value over which there is a ripple riding over that and that's when we can able to ensure that the switching cycle average

variation is having the sinusoidal behavior. And thus we get the actual current which is having sinusoidal variation and high frequency ripple is riding over that. Now there we see that at all the times we have assumed that at all the times the inductor current is continuous in nature that means it goes let's say this is the this is the waveform we are getting for is so the inductor current is actually going in some positive having positive slope coming down in negative slope and it is not coming down to zero.

The inductor current is always non-zero except near to zero crossing that is again the I mean that is a requirement of that but in the other than the zero crossing near I mean other than the time period away from the other than away from the zero crossing points you still have the inductor current which is continuous in nature it is not going to zero. And to ensure that this is there, what we have done, we have seen the closed loop control where we require a very important thing, which is the multiplier block. So, in case of bridge boost PFC case, we have multiplied with the $|\sin \sin \omega t|$, while in case of bridgeless PFC, we have directly multiplied it with unit $\sin \sin \omega t$ or you can say that $\sin \sin \omega t$. So, in both the cases inside the controller or let us say we are implementing that controller using the analog components we require a multiplier block and that particular multiplier block is sometimes causes I mean the huge computation burden or you can say that sometimes you require more memory to handle that multiplier I mean the result of that multiplier block and also sometimes it also you know time consuming is also there.

So, we sometimes require a high-end microcontroller to handle this multiplier block to do the multiplication and that is why sometimes it is also called as the multiplier control approach. Where you are actually sensing the $\sin \sin \omega t$ or $|\sin \sin \omega t|$, or you are actually generating the unit sin with $\sin \sin \omega t$ or $|\sin \sin \omega t|$, and multiplying it with the output of the voltage block or voltage controller block. Then we along with this multiplier block, there is also one more problematic case is which is the generation of that unit $\sin \sin \omega t$. and that unit sine waveform the generation of that unit sine waveform has to be such that it is closely following the actual input ac voltage. So what you can say there should not be any phase angle between that units and ωt and the v_{s,p_k} and ωt which is been there in the grid and we know that the generally this grid voltages have variation in frequency have also variation in voltages and those are obviously those are maintained within the tolerances but there is a variation we cannot say that

at every time it is the pure sine wave having v_{s,p_k} in the positive direction, $-v_{s,p_k}$ in the negative direction. So, we cannot able to sense the exact peak and we could not able to say that the entire frequency is actually the nominal frequency. So, that is why how we can generate the unit sin $sin\ \omega t$ waveform and that is when it is one of the research topic to generate that unit sine waveform or you can say the unit sin signal. And it is also very complicated because you have to make the high-end PLL's you have to do you know high-end filter circuits you need you require high-end computation block to actually estimate or to actually you know generate that unit sine waveform and then after doing that we also have to do the multiplication with the output of the voltage block which again takes good amount of memory space and also the computational effort.

So, that is why sometimes either you require a very high end microcontroller or if you wanted to do in the low end microcontroller then you must have that required computational time available with you to actually perform that particular multiplication. That means sensing the actual voltage signal and then from the actual grid voltage we have to generate the unit sin either unit sin $sin\ \omega t$ or ωt |or modulus of unit sin signal or sin signal and then multiply it with the output of voltage controller block. So, doing those things are very complicated require computation you require high performance microcontroller to do those computation. Now to avoid those things we one can also do one simple I mean one voltage follower approach where instead of making this inductor current having the continuous conduction mode we can make sure the inductor current will have the I mean we can ensure that inductor current is following your input voltage and making sure that you do not require any multiplier block. So, to do that one way by which it can be done is making sure this converter operates in it in a I mean this system operates in a discontinuous conduction mode.

So, let us try to understand what the discontinuous conduction mode of boost PFC is. Now, in discontinuous conduction mode, We know that in this particular circuit, our v_d is

$$v_d = |v_s|$$

and we can also know that our i_s, or the current drawn from the grid, $i_s = i_L$ when $v_s > 0$ and $i_s = -i_L$ when $v_s < 0$. So, in other words, if we can know the i_L value, we could say

what kind of input current we can expect to be drawn from the source. Now, let us try to see how our discontinuous conduction looks like.

So, let us take one or two cycles as an example. One of the, let us take in one of the switching cycles, T_S switching cycle. Let us see my inductor current, which is there since we have a discontinuous conduction mode. That means the inductor current is going to 0 in every switching cycle and starts from 0 at the start of the switching cycle whenever the positive voltage is applied across the inductor. So, if we assume that it starts from zero, if the inductor current starts from zero, it goes to some peak value. Let's define this as, let's say, I_{pk}.

And then this particular current—so this is the case, you know, at this point, you can say that let's define this point as T_{S1} on, where at that T_{S1} on, my switch S1 is on. Because whenever S1 is on, you are directly applying v_S voltage across this inductor, and you will have the positive slope. And then, after T_{S1} on duration, this switch S1 is switched off, and S 2 is on. And that's when you will start applying $v_S - V_O$ voltage across this v_L. And since $V_O > v_{S,PK}$, we are applying a negative voltage across this inductor.

And that's when inductor current falls down. And since we are talking about this continuous conduction mode, we will ensure that this inductor current goes to 0. Now, this time, let us define this time as T_{S2} on. And then, let us say from this point to this point, there is no induction current flowing through the inductor and that is when there is no you know instantaneous current drawn from the source during that time and then again after this T_S duration you know one of the switching cycle we see that again my inductor current will again S1 is on and then again we will have this maybe some different I_p will be there we will see what could be the peak and then again it falls down again zero and then again it goes up. So that kind of waveform is there. So now let us see in that particular T_S duration what are the voltages which are applied and how that voltage and currents are dependent on each other. So if we look very carefully in this case, when it is going from 0 to I_p.

 So we can write down v_L is,

$$v_L = L\frac{di}{dt}$$

So, di is always going from 0 to I_p, so we can say

$$v_L = L\frac{I_p}{dt}$$

which is nothing but T_{S1} on, is nothing but equal to v_L, and during T_{S1} on duration, whenever the switch S1 is on, you are only applying v_S, so you are applying the v_S voltage across this, and that you can write down this v_S is

$$v_S = L\frac{I_p}{T_{S1}}$$

and we know that I can write I_p is nothing but, you know, this v_S is nothing but, you know, a v_d, which is nothing but $|v_S|$. So we can say $|v_S|$, and this is nothing but I_p is

$$|v_S| = I_p = v_S\frac{T_{S1,on}}{L}$$

And if we make sure, if we can ensure that our $T_{S1,on}$ is constant, then we can say that my if $T_{S1,on}$ is constant, then the peak current or the peak of the i_L current, I_p which is peak of inductor current, follows the modulus of v_S variation or you can say that the your AC voltage. So, we can see that our peak value peak inductor current is following nothing but the input v_d which is nothing but the $|v_S|$. So, we can say that our peak is varying sinusoidal in nature same as that of the AC voltage. However, with different amplitude but it is varying in the peak is varying in the sinusoidal manner. So, I_p is varying in sinusoidal manner. Thus we can say that the input current peak is following the input AC voltage. Further if peak is following the voltage then there is a possibility that the average variation of current in a switching cycle is also following the input AC voltage. And if that thing happens, then I do not need any multiplication on any high computational burden blocks. And thus can able to ensure that my converter is actually following the voltage or you can say the converter is operating in the voltage follower mode.

And we know that our input voltage is varying sinusoidally. So, the current which has been drawn is also following the input AC voltage. So, let us take our discussion ahead. So, we

know that my I_p is always varies with the $|v_s|$.. And let us try to calculate the average variation of i_L. So, let us calculate average variation of i_L.

Over the T_S period. That average variation over the T_S period. We can write down. If we know that we are actually having this kind of variation. So every time it starts from 0 goes to this I_p value.

Obviously, this I_p value varies with the input voltage. But it goes to the I_p value and then again comes back to 0. So, we can say that during this time, I mean, I can just write the average value is nothing but. So, we can write half.

So, we can take half times,

$$\langle i_L(t) \rangle_{T_s} = \frac{1}{2} \frac{|v_s(t)|T_{S1,on}}{L} \times \frac{(T_{S1,on}+T_{S2,on})}{T_S}$$

$$D_1 = \frac{T_{S1,on}}{T_S}$$

$$, D_1 = \frac{T_{S2,on}}{T_S}$$

$$\langle i_L(t) \rangle_{T_s} = \frac{1}{2} \frac{|v_{s'}(t)|T_{S1,on}}{L} \times (D_1 + D_2)$$

$$\langle i_L(t) \rangle_{T_s} = \frac{1}{2} \frac{|v_s(t)|T_{S1,on}D_1T_S}{L} \times (D_1 + D_2) \tag{1}$$

$$|v_s(t)|D_1T_S + (|v_s(t)| - V_o)D_2T_S = 0$$

$$D_2 = \frac{|v_{s'}(t)|}{V_o-|v_{s'}(t)|} \times D_1 \tag{2}$$

Substitute 1 in 2

$$\langle i_L(t) \rangle_{T_s} = \frac{1}{2}|v_s(t)|D_1T_S \times \left[D_1 + \frac{|v_{s'}(t)|}{V_o-|v_{s'}(t)|} \times D_1 \right]$$

$$\langle i_L(t)\rangle_{T_s} = \frac{1}{2}|v_s(t)|D_1^{\,2}T_S \times \left[D_1 + \frac{|v_{s'}(t)|}{V_o - |v_{s'}(t)|}\right]$$

$$i_s(t) = i_L(t),\ v_s > 0$$

$$= -\,i_L(t),\ v_s < 0$$

So if we look very carefully, this $|v_{s'}(t)|$, which we are getting the average variation as $|v_{s'}(t)|$. So this we can, if we are writing for i_s. So we can write down that the average variation of i_s during the Ts duration is

$$\langle i_s(t)\rangle_{T_s} = \frac{1}{2}|v_{s,pk}\sin\omega t|D_1^{\,2}T_S \times \left[D_1 + \frac{V_o}{V_o - |v_{s,pk}\sin\omega t|}\right]$$

So, we see that this average variation of $\langle i_s(t)\rangle$ is varying sinusoidally if and in this if we can if we keep D_1 and T_s constant, that means the T_{S1} is kept constant. So, we can ensure that we can ensure that average variation of $i_L(t)$ in the switching cycle actually varies with that this variation is nature. So if we if we see this waveform what we will see is that let's say our vs is is having something like this this is my yes or let's say $|v_s|$, in one half cycle only we will see, so my my this variation you will have positive coming to zero then goes down then positive coming to zero, then zero then positive coming to zero zero, positive coming to zero, for some time it is your positive coming to zero like this. So if we see that average variation will be having some something like this we will get the average variation and this is your nothing but since our this is nothing but is I mean i_L this is nothing but your i_L and if we see the peak the peak of i_L is actually varying sinusoidally having the maximum value at the peak of the $|v_s|$, and if we see this is the average variation this is the $\langle i_L\rangle$ variation over Ts and this is close to sinusoidal it is not actual sinusoidal but is close to sinusoidal it is slightly away from sinusoidal. But however, the variation i_s of a sinusoidal behavior but it is not exactly $\sin\ sin\ \omega t$ or actual sinusoidal variation. However, the variation is looking close to sinusoidal in nature.

It is primarily because you have modulus, $v_{s,pk} sin\omega t$, also at the bottom. So, because of that we have switching cycle average variation closer to sinusoidal and not exactly sinusoidal. However, the peak current i_s varying sinusoidal in nature and we are not requiring any multiplier block or any you know sense or generation of this unit sinwt block. So the advantages with this what we will get if we try to see the closed loop solution. Further the closed loop solution will be very simple you just sense the output voltage Just define the V_O reference output through the controller directly; it goes to the modulator block where we make sure that the turn on period of this S1 is kept constant and the switching frequency is kept constant that means turn on time of S2 is varied accordingly and that's when this modulation will give you this modulator will give the output as as pwm pwm of S1 and pwm of S 2 switches.

So, here you are not requiring any multiplier block. You do not require any generation of $sin\omega t$ block. Also, you do not need to have any closed loop current control block as well. Automatically, the current which is being drawn from the source is actually following the AC input voltage or AC voltage. So, the advantages what we get is that with this particular setup is the current drawn from the source follows the AC voltage automatically, and the use of multiplier dual loop and the unit $sin\omega t$ waveform can be avoided. Okay, also, one more advantage you will get. See, if you look very carefully at every instance of time, whenever S1 is on and whenever S 2 is turning off, at that time, the current, the i_L current, is zero. So that means you will also have reduced switching losses. Switching losses are reduced because whenever you are turning on S1, it is turning on with zero current, and whenever S2 is turning off, it is turning off with zero current. And if, let's say, instead of S2, one is using a diode, so the reverse recovery losses are nearly zero in case of, you know, DCM operation of the boost PFC case. So that is again one advantage we will have. So, I mean, reduced switching loss or lower switching loss if we are using an active switch or if a diode is used in place of S2, the reverse recovery of the diode is nearly zero.

Because it is turning off with zero current. Now, the disadvantage of this thing is. The disadvantages of this topology are. Obviously, the input. I mean, the switched average variation of current.

Or you can say the average input current is close to sinusoidal. And not actually sinusoidal. So you will see, you know, the THD is more in this second. We will also see that since the peak is varying sinusoidally, as well as the average is not sinusoidal but close to sinusoidal, so what you can see is that the ripple is more. And because the ripple is more, you can see that the inductor current ripple and the switches have higher RMS currents. So, RMS current of S1, S 2, L, D1, D2, D3, D4 are more. And you will also see one more important thing when it is switching off. So you can see that at this point, my S1 is on, and at this point, my S 2 is on. So you will see that the S 2 switches on with higher currents. Or you can see that S1 here, the S1 turns off and S 2 turns on. So you can say that the S1 turns off with higher current, S1 turns off.

Higher current thus, I mean, sometimes has more switching loss, or we need to ensure that the gate driver or the parasitic does not get activated because of that. So, this is the advantage with this DCM operation or discontinuous conduction operation of this boost PFC, which is We can automatically ensure that the current drawn from the source is actually following the AC voltage source, and the peak of the current is varying sinusoidally. However, the average current is not sinusoidal but is close to sinusoidal, which indicates it has higher THD as compared to the continuous conduction mode. Because there, we have the fundamental component and then the switching frequency component, and the switching frequency component is very far away compared to the fundamental component. Then we see that our ripples are more in this one, and that is when the RMS current of these devices is particularly higher. One more advantage we get because of the DCM: if my S 2 switch is realized with a diode, you can see that the diode turns off. The reverse recovery losses or reverse recovery losses of the diode are nearly zero.

Reverse recovery losses of the diode are nearly zero. And one more thing we will see when doing the closed-loop operation: we do not need any dual-loop structure, we do not need any multiplication factor, or we do not need any unit sine waveform generation. Here, we just need one loop where we ensure that the output is actually following the reference, whatever we set the output voltage reference to. Because automatically, the current drawn will be following the voltage.

So, this is the advantage we get by the DCM operation of the boost PFC converter. Thank you for patiently listening to this lecture.