

CHARGING INFRASTRUCTURE

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Week-02

Lecture-9

Lec 09: Single-phase Boost PFC Converter - I

Hello everyone, welcome to Lecture 9 of the NPTEL lecture on charging infrastructure. In this lecture, we will study some functionalities related to the single-phase boost power factor correction converter. So, in the last class, we revisited the single-phase full-bridge diode rectifier, which is basically an uncontrolled rectifier. We also saw how the operation of that full-bridge converter changes when we use a capacitive filter.

And we gained certain understanding. The first understanding we obtained is, we could draw unity power factor current from the source if we could have a resistive load at its output. However, to achieve this, we could not get a constant or nearly constant output DC voltage, so for that, we added a capacitive filter. And because of adding the capacitive filter, the current drawn becomes peaky in nature, obviously deviating from sinusoidal and also having non-unity power factor characteristics. We also saw that, although adding the capacitive filter allows us to get an output voltage varying within permissible limits, the components of the converter, like diodes and capacitors, need to be oversized to handle the peaky currents drawn from the source. To combine both aspects, we understood one thing: let us have the diode rectifier at the front stage, so we can have a power converter. This power converter can be operated in such a manner that its input impedance is resistive in nature. Then, we can ensure that the current drawn from the source is sinusoidal in nature and has the same phase as the input AC voltage, thus achieving unity power factor operation. So, let us see if we use different power converters, we can input different kinds of converters and achieve a unity power factor current draw. Thus, this kind of converter is also called a power factor correction (PFC) converter, where we have a power converter placed at the output of the full-bridge diode rectifier. This type of overall converter, where we have the full-bridge rectifier

and the power converter cascaded with them that kind of converter we will see now in this power converter one can have boost converter boost dc dc converter one can have the flyback based dc dc converter different power converter configuration can be used here while which ensures two things one is unity power factor current drawn from the source as well as the output voltage is kept constant within the permissible limit so one of such commonly used power factor correction converter is boost PFC converter so let us see the functionality of this converter and let us see how this particular converter works and try to understand some of the expert related to this converter now if you look very carefully this particular converter has a full bridge full bridge diode rectifier at its front end at its front side or you can say that at the first stage and then followed by if you look very carefully followed by a boost converter where we have the inductors let us define this inductance as L and we have the half bridge commonly used or you can say the fundamental building block of any voltage source converter which is an half bridge and having a capacitive filter let us define it by C and the load R_L and because since we have put the capacitance it is having the output voltage whose nominal value let us define as the V and having a ripple over that now here since this is a boost converter which is the current ' I ' which is coming out of this converter some current will go into the ' i_c ' and the average value of the current will be I_L which is going through the load which is going through this load R_L .

Now if we see very carefully this boost since we have used boost converter let us quickly look how the boost converter look like as you must have gone through in your first level powertronic course we have a boost converter which looks like dc-dc boost converter which looks like this switch S_1 so here i am drawing a very generic switch it could be a mosfet it could be igbt or thyristor if you want to have So this switch is there then what we have is we can have the diode D and having the capacitance C which is again feeding the load R_L and we have this L and we have B input. And we can actually replace the diode with more generic switch. It could be the MOSFET with body diode, IGBT with freewheeling diode or it could be just a diode. So we can make this particular converter connected in a manner.

So let us take the generic switches and we can make this converter like this. This is the same converter which we have drawn here so here what we have is we have the diode bridge rectifier

and then followed by or cascaded by a boost converter now if you look very carefully we know that in this particular full bridge rectifier we have you know this

$$v_s = V_{s,pk} \sin \omega t$$

which is $V_{s,pk} \sin \omega t$ putting I mean coming as an input now in this particular converter we know that in the positive half cycle this D1 and D4 gets forward bias and as a result of which this v_d is nothing but equal to v_s or v_s voltage which is been which is been there in the input side and in the negative half cycle is the D2 and D3 which get forward biased and the output v_d is nothing but equal to negative of the input voltage v_s , so if we look how the output voltage waveform look like or the v_d voltage look like so we have this $V_{s,pk} \sin \omega t$ and similarly since in the positive half cycle D1 and D4 gets forward bias we have the let us say this is v_s in positive half cycle the v_d value will be the same as v_s value in the negative half cycle because D2 and D3 get forward bias.

We have the voltage which is just negative of the v_s which is at the input. As a result, what we will get is we have the rectified DC voltage, or you can say that the $|v_s \sin \omega t|$, which is what we are getting at the v_d . So, v_d we can say that $|v_s(t)|$, and that we can say that $|v_{s,pk} \sin \omega t|$, v_d will look like this.

Now, if you look very carefully, since this voltage is implied over here, let me define this point as point A, this point as B, and let us define this point as C and this point as D. So, if you look very carefully, in this particular space, the AB, the potential at point VAB, which is nothing but the v_d , is uncontrolled and is defined by the input voltage which is applied at the input of this full-bridge diode rectifier. So, this is uncontrolled, and the variation of this will look like this. However, the voltage at C to D, or you can say the V converter voltage (V_{conv} , voltage), which is at the other side of the inductor, this particular voltage we have the control that we can actually vary this V_{conv} , voltage. Now, how we can vary this V_{conv} , voltage? What we can do is we can actually, let's say if this is the converter, this half-bridge, if we have this half-bridge as a converter, let me

draw this S1 or this S1, this is S2, see and let's say here we have the potential wheel coming across here.

Now, if you look very carefully in this particular converter, if you turn on the S1 switch, what happens is that the voltage of the CD, the voltage of the CD is equal to zero. And if we turn on this if we turn on this S2, then the potential which is applied through the V through the CD point is nothing but your V_o . Thus, we can vary the turn-on time of this S1 and S2 switch, and thus as a result, on an average sense, we can generate the V_{conv} , voltage which is which is having some value, and we can then vary this turn-on period of this S1 and S2 switch. Thus, we can get the average variation of this output of this half-bridge, which is V_{conv} , varying such that we can make sure the current drawn from this side is also following the pattern which v_d is following. So, since on this side point AB, our v_d voltage is defined by the operation of this full-bridge rectifier and the input AC voltage. On the other side, from the node C and D, we can apply the variable voltage in an average sense, and that average variable voltage is such that the average inductor current in a switching cycle, which is the same as that of ' i_d ' current,

will also be following the same pattern as that of v_d . Thus, as a result, we can get an average idle current which will be following the v_d pattern. And thus, since the switching period average i_d current looks like this, our ' i_s ' current, which is equal to i_d current in the positive half cycle, and equal to negative ' i_d ' current in the negative half cycle, will look like this in an average sense.

This is the V, and thus as a result, we can say that we are drawing the unity power factor current from the grid or from the AC voltage source. So, what we need to do is this particular half-bridge is switched with varying turn-on times of S1 and S2 switch in such a manner that the average voltage in a switching period, which is coming from this side V_{conv} , is varying in a fashion such that the average current in a switching period, which is going through the inductor, will be having the same variation or you can say that having the same $\left| v_{spk} \sin \omega t \right|$, variation as that of v_d .

Along with having the same phase, that means no phase lag or lead between the v_d and switching period average value of I_L . Now, if you look very carefully, this voltage which is applied through V converter can vary by changing the turn-on time of this S1 and S2 switch, and thus on an average sense, we can apply any voltage between 0 to V_o at the point C and D. And that's how we can control the current flowing through the inductor by controlling the voltage across it.

One side voltage is constant which is defined by the AC input voltage. However, on the other side, we can have the variable voltage or we can have the voltage which can be controlled by the operation of S1 and S2 switch and in such a manner that the average value of I_L which is equal to current i_d will be following the same variation as that of v_d , along with the maintaining the same phase. And thus the current drawn from the input AC voltage source is also having a sinusoidal variation in a switching average along with the unit power factor operation. Let us try to see how we can operate this particular converter and how what switches we can have S1 and S2 switch and how in the different cycle it will work. So, let us see how this boost PFC works and in this boost PFC there will be certain consideration which one need to take some of the considerations are first consideration is obviously the switching frequency of of S1 and S2 switch

is greater than the, is much greater than supply frequency. That means one can say that the f_{sw} is very, very much which being the switching frequency f_{sw} of this S1 and S2 switch is very, very much greater than f_s . The reason why we have taken this particular consideration is when we take this particular consideration, which means that let us see since our switching frequency is very, very much greater than the f_s frequency. So, if we see our wheel voltage, if we see our v_d voltage, now this v_d voltage is obviously this particular frequency is nothing but the T, which is nothing but the time period is nothing but $1/f_s$, and if we consider switching frequency to be very very much greater than f_s that we can ensure that the t_s period which corresponds to $1/f_{sw}$ is very very much smaller than T where we can say that T_s is nothing but $1/f_{sw}$.

$$T_s = \frac{1}{f_{sw}}$$

so, what it indicates the switching instances will be very small in instances we have and, in these instances, we can say that the v_d voltage or you can say which is nothing but $|v_{s(t)}|$, is nearly constant during one switching period.

$$v_d = |v_{s(t)}|,$$

So, that is this particular consideration which is f_{sw} is greater than f_s will lead to the point that the wheel which is nothing but the $|v_{s(pk)} \sin \omega t|$ is nearly constant because you know these instances are very nearby. This particular time period is very nearby is very much closer to which as a result of is this variation which is there is very small is this time period is if this time period is very small then we can make ensure that this variation is very small or we can say that this particular v_d voltage is nearly constant during one sampling or one switching period.

Now this will give us some some advantage because if we assume that $v_{s(t)}$ is constant in a switching period then accordingly we know that what value of this v_{conv} has to be applied from this half bridge or from this half bridge converter such that we ensure that this I_L current or which is nothing but equal to ' i_d ' current is also having a some average value in a switching period which is varying same as that of v_d which is the $|v_{s(pk)} \sin \omega t|$. So, thus considering this particular consideration let us see how our converter look like at a different time instances or a different modes of operation of this particular converter. So, let us assume the let us take the variable D which is nothing but D is the duty ratio of switch S1 at one of the switching period in a half cycle of input AC voltage. Since the v_d in a switching period is constant, so we can take this D as a constant value. This duty ratio tells for how much time the switch S1 is on in a switching period.

And corresponding to that, we will take the v_s , modulus $v(c)$ is the v_d voltage, at same switching instant or at one of the switching instants which has the same duty which has the duty

ratio D . So, let us see how the converter works or let us see how the particular converter when it is in operation how the different modes look like let's see in positive half cycle in positive half cycle we will only consider the positive half cycle case where the $D1$ and $D4$ are forward biased and because of that what we will see is that during and let us see in that particular positive half cycle that means in this particular instance we are only considering this particular instance In this particular period, one of the switching periods we have taken where at that point, this switch $S1$ has a duty ratio given by capital D and the v_d value is nothing but the $|v_s|$ at that particular instant. And since this period is very small as compared to this period, we can assume that this $|v_{s(t)}|$, is really constant and we can also assume that the duty ratio will be constant in one switching period.

So, during that time, let us say in that particular positive half cycle during time period DT_s where T_s is nothing but 1 divided by f_s switching.

$$T_s = \frac{1}{f_s}$$

During this T_s , $S1$ is on. And since $S1$ is on obviously the $S2$ has to I mean the $S2$ need to be turned off otherwise this particular output or this particular V_o . So this particular bridge gets short circuited if both the switches are on. So if this is on this has to be off and if this is on this has to be off.

So, in this particular period during ' DT_s ' period we assume that $S1$ is on. Since $S1$ is on so the circuit will look like this $D1$ is on $D2$ is open circuited $D3$ is reverse bias $D4$ is forward bias so it is you can draw in that way $D1$ $D4$ $D2$ $D3$ and this input voltage is coming over here this is coming over here. Thus, this the one which is been here through one we have you know as since $S1$ is on so this $S1$ is on and since $S2$ is open so we will keep this open and thus capacitance and we have resistance r_l So, if we look very carefully, the voltage across this inductor is nothing but if this is v_d and if this is v_{conv} .

So, we are actually having the zero voltage on the other side and the voltage across this is nothing but $|v_s|$. So, in the during DT_s period, Dt_s period where T_s is nothing but equal to $1/f_s$ switching. what we are having is we are actually applying since this is short circuited we are applying $|v_s|$, which is the value of this v_s during one of the switching period instances which will be applied, so this and since this particular time period is very small, this particular $|v_s|$, is nearly constant. So, at that point V_L you are applying a constant $|v_s|$, voltage across here. So, if you do the KVL in this loop, you will have this V_L is nothing but equal to $|v_s|$. So, this is nothing but equal to modulus of $|v_s|$.

$$v_L = |v_s|$$

However, if we look very carefully, since we have this positive voltage applied across this inductor, we have this rising, you know, rising current through the inductor because V is equals to $L di/dt$.

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

And that implies my di/dt is nothing but modulus v_s/L .

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

It is having a positive slope. equals to modulus of v_s/L where L is nothing but the inductance L which is being kept between this full bridge rectifier and the half bridge of the boost converter so this we have the slope we have the rising slope since my S1 switch is on so you can see the current through the S1 switch is rising we will be following the same current as that of the idle current however since the S2 switch is off you will see the S2 switch is not at all conducting any current and that's when the current through the S2 switch is zero. And during this period, we see that the entire V_o voltage entire V_o voltage is appearing across this S2 switch because because since this is S1 is on so the entire this V_o voltage is coming across this S2 switch. So, the switch S2 is is to be such that it will block the voltage in one direction or one polarity of voltage need to be blocked because the output is dc.

So, the switch S2 has to block one polarity of voltage when it is off so S1 is on S2 is off so since this S2 switch is off so it has to block the entire V_o voltage and if we define the polarity of this S2 switch is of the form plus then we can write v_{s2} or the voltage coming across the S2 switch is nothing but minus V_o . So, that is what we get that whenever the S1 is on the S2 has to block the output which is again a dc voltage has to block V_o and we can say that if we define the polarity of S2 in this manner we can say that v_{s2} has to block that $-V_o$ voltage across it if the polarity is defined in this manner so this is the case when we have our during DT_s period so we can say that if we try to write the inference during these DT_s period. So, during DT_s period S1 conducts or S1 conducts and conducts current in one direction and S2 blocks Voltage of one polarity given by v_{s2} , $v_{s2} - V_o$. Now, let us take the condition during in the positive half cycle during $(1 - D)T_s$ period.

So, when we consider the condition $(1 - D)T_s$ period during that period my instead of S1 switch my S2 switch is on. My S2 switch is on and thus it will be and my S1 switch is off we will see what is the value of voltages as we go along within the positive half cycle during $(1 - D)T_s$ spirit that means remaining period of the switching cycle the condition of the circuit will look like so instead of the S1 switch now we have the S2 switch which is on so let us draw the S2 switch so here instead of of this now S2 switch is on and the S1 switch is kept is kept open since the S1 switch is kept open and S2 switch is on so we can apply the KVL in this particular loop we can apply the KVL, and if we apply the KVL, what we are going to get is we will see that the voltage across, what we will see is that the v_L voltage will be nothing but modulus of $(v_s - V_o)$. This value is V_o .

$$v_L = (v_s - V_o).$$

So, we will get the current or the voltage across the v_L as modulus of Vs minus V naught.

$$v_L = |v_s| - V_o$$

Since we get modulus of $(v_s - V_o)$ and if we assume that the V_o is greater than $|v_s|$, which we will see as since it is a boost converter, obviously the output voltage or you can say the output voltage is always greater than v_s . So, that is when the v_L is negative and that is when we can say that di/dt is nothing but $v_s - V_o$, $|v_s| - V_o$ divided by L and this is actually a negative quantity.

$$\frac{di}{dt} = \frac{|v_s| - V_o}{L}$$

So, thus we can see that the slope, you can say that negative of V_o minus and this one divided by L.

So, thus we can see that this particular slope is a negative slope and that's when you can see that the current will be in the will be falling and this current since your S2 switch is on. So, the current will be flowing through the switch S2 while the since the S1 switch is off there is no current through this switch S1 and since my S1 switch is off. off let me define this polarity as this so since my S1 switch is off so the it will block the v_{s1} is nothing but V_o voltage so during $(1 - D)T_s$ period you see that S2 conducts current in one direction and that will be from as we mentioned the positive and negative polarity it is going from this positive polarity to from the bottom to the top in this direction that is when it is conducting in one direction and S1 blocks voltage of one polarity which is nothing but v_{s1} nothing but V_o .

This we can define as v_{s1} . So, we have understood that S1, so if we try to draw the S1 switch, so for S1 switch, if we try to see how the S1 switch will be with respect to current and voltage across the switch. For the S1 switch, it carries current in the positive direction when it is turned on. when it is turned off it is blocking the voltage in positive direction so that's why the if we draw the I-V characteristic of the ' i_d ' switch it will look like this similarly for the S2 switch when it is on it allows the current in one direction or which is the positive direction is from bottom to top and it will block the voltage which is one polarity voltage which is $-V_o$. So, the I-V characteristic of S1 and S2 switch will look like this since the I-V characteristic S1 is in the first

quadrant we can obtain the switch we can realize the switch using any MOSFET with IGBT or one can also use BJT as well.

Similarly, for S2 switch since it is in the second quadrant this I-V characteristic one can realize the switch using diode or one can use the MOSFET and use the body diode of MOSFET. So that's when you can realize this switch S2 and S1 accordingly. Now since if you look very carefully this the I_L current which is going which is having positive slope during DT_s period and having the negative slope during the $(1 - D)T_s$ period it will have certainly it will have some average value. And this average value, if you look very carefully, this particular average value, if we can make sure this average value varies in the same manner as that of the v_d , then we can ensure that the variation of average ' i_d ' current in a switching period and variation of v_d is the same in the half cycle of input AC voltage.

Also, we can also see that this particular average value of current, how we can get the different or the variable average value of the current this we can get by varying this duty ratio that means the varying the turn on time of this S1 switch and S2 switch such that the current average value of current is following the same behavior as that of the v_d which is you know $|\sin \sin \omega t|$. So that's when we come to conclusion that we need to make sure this duty ratio is varying in every switching instant and that variation will be having some sinusoidal variation in such a manner that the current, the average current will be also varying in the same manner as that of the v_d which is nothing but the $|\sin v_s \sin \omega t|$, and that is when we can ensure that the ' i_s ' current which is drawn from the source will also be having a sinusoidal behavior or having the unity power factor. So, thus we will be we need to find out what will be how this duty ratio will be varying that will we see in the next class or in the next lecture.

Thank you.