

CHARGING INFRASTRUCTURE

Prof. Apurv Kumar Yadav

Department of Electrical Engineering

Indian Institute of Technology Roorkee

Week-05

Lecture-21

Lec 21: Flyback Based PFC Converter

Hello everyone, welcome to the lecture number 21 of this NPTEL lecture series on charging infrastructure. where we are dealing with different aspect of EV charging systems. In today's lecture, we will see flyback based PFCs converters. In the previous discussions, we have seen boost converter based Pfc's converters where we have diode bridge rectifier in the front end and then followed by we have a DC-DC boost converter. So, and we can able to ensure the current drawn from the source is sinusoidal by ensuring that this ' i_d ' the average variation of this ' i_d ' is having the rectified variation.

If we ensure this is there then automatically our current drawn from the source is also the unity power factor or the sine wave having a zero phase angle between the current and the voltage. then we have seen the its derivative which is nothing but a totem pole PFCs where we do not require any diode bridge at the first stage we directly connect the inductor to the active bridges again we can either use this diode one diode half bridge or we can either use active half bridge you can say using active switches again here the concept remains the same we apply the voltage across inductor in such a manner that the average current drawn from the source is sinusoidal and having the unity power factor current drawn. So this is what we have studied we have also seen the average current control where we were actually controlling the average value of the current drawn from the ac source and then we have seen the voltage follower mode where we have seen that converter will be in the DCM mode or discontinuous conduction mode and by doing the discontinuous conduction mode automatically the peak of the current will be having the sinusoidal variation and that's when we can say that the average current is also be nearly closer sinusoidal variation. Now the advantage with that is in DCM mode the advantage is that

DCM mode means discontinuous conduction mode. The advantage is we do not have to put any multiplier while doing the closed loop control. It is a simpler closed loop control. We can implement it in any controller and also we do not need very high end controller to implement those DCM mode controls. And the current will be having the voltage follower mode where we do not require any multiplier or any high end computation.

Now one question can be asked can only this be the method by which you can actually have the constant or regulated voltage at the output while drawing unity power factor current from the source. There are other method also which can be used for example flyback based Pfc's converter in flyback based PFC's converter what we have is we have the diode bridge rectifier at the front of the first stage. We have a diode bridge at the first stage and then followed by what we have is we have the flyback based converter that switch can be take let's define this as one switch and here again we will define the dot polarity in such a manner that we have dot (\cdot) polarity here and then this inductor is and then this inductor is actually wanted on a core having another winding whose dot polarity are arranged in the manner shown over here and then followed by this we will have a diode let's say diode D_v and then we can have a capacitor C and then finally we have a load resistance R_L and here we have the voltage nothing but V_o voltage which is coming over here and we have we can define $D_1 D_2 D_3 D_4$. Let us take the inductor these two inductors have the turns ratio in n raise to 1 ratio, where n is there is the winding let's say this winding name is p and this winding name is s. So, p has n number of turns while s has just one number of turns.

And let us say if there is only one winding which is made over here, it has the inductance L. Refer to obviously refer to the primary side of this transformer. And if you look very carefully, we again have this v_d voltage which is coming over here. And we have again v_s voltage which is nothing but $v_{s,pk} \sin \omega t$. And this v_d is nothing but $|v_s|$ which is nothing but the rectified AC at this across the diode bridge output. Now, if you look very carefully in this particular circuit these two inductors are bonded on the same core that is why they are actually coupled together and what happens is that

Again, here again the same thing will happen. My duty ratio which is ratio of the time duration in the switching period is the time during which this S_1 is on and in $(1 - D)T_s$ period, $(1 - D)T_s$ period, my D_B will be on and S_1 will be off. So, here we have two state since we have here rectified dc voltage here and output is your fixed dc V_o is a fixed dc we we must ensure that this S_1 has to be switched in such a manner that we are getting a constant voltage at the output. So, again we have the duty ratio which is we can define $d(t)$ we have the $d(t)$ which is nothing but duty ratio of switch S_1 that that varies with time t and here again this switch S_1 is switching with frequency f_{sw} where f_{sw} is very very much greater than f_s where f_s is the line frequency which is generally 50 Hz or 60 Hz now again we can apply the volt second balance on this coupled inductor. So, here what we can do is we can now say that during DT_s period during this period the S_1 is on. Now if we look very carefully since the S_1 is on so our circuit will be let me here just draw the v_d voltage which is nothing but the $|v_s|$ what we have is we have something like inductor here and this S_1 switch is on so since this S_1 switch is on S_1 switch is on so this S_1 switch is on here we can now this is the v_s , S_1 switch is on and here the dot polarity is here and what we have is we have another dot polarity so since the S_1 switch is on here we are directly applying v_d voltage and since here v_d voltage is there on to the coupled inductor which is on to the other winding which is actually bonded on the same core what we have is we have plus minus a polarity voltage coming over here and then this which results in since the negative polarity is applying onto the anode of this diode that's when this diode D_B is open circuited or reverse bias and what you have is we have a circuit something like this where we see that our Our this capacitor C is nothing but actually supplying it to the load. And during this time, we can say that during DT_s period, we can say that the voltage applied across the inductor, we can say that v_L is nothing but $|v_s|$ voltage applied during $d(t)$, during DT_s period. okay so this is the thing during DT_s period now let us take the next case how our circuit looks like when we have $(1 - D)T_s$ period when your S_1 is off during $(1 - D)T_s$ period yes

period what happens is that my S_1 is off and let's say when S_1 is off let me all draw from here v_d now S_1 is open

because of this S_1 is open what happens is what happens is because this S_1 is open. Since this S_1 is open what happens is that the instant during which this S_1 is open what happens is that there is $d\bar{i}/dt$ which will be coming across this which is in the negative in the negative direction that means you have voltage induced in this way which is

$$V = L \frac{d\bar{i}}{dt}$$

and because of this positive negative polarity here we have a negative and positive polarity that's when this diode D_B is forward biased and then you have the current which start flowing to the load in this in this manner. So, here in the previous case the current is going from dot to non-dot and thus as a result of which the flux in the core gets build up while in this case again in order to ensure the continuity the current through the inductor cannot change so that's why on the other winding the current will again start from dot to non dot however in this case since there is no voltage source is been connected to the winding which actually build up the flux in the core in this case the it is the core which is actually driving the load and that's when the flux in the core get de-energized in the previous case it core was getting energized in this case core will get de-energized, or the flux will then decay out or you can say that the flux which was got builded in the core will now come back in such a manner that the flux will come back to its original point the current will be such that we have the flux gets goes to zero and we will be ready for the next cycle to have the again flux build up in the next cycle so what we have is in this case in $(1 - D)T_s$ period $(1 - D)T_s$ period the S_1 is off and because since that S_1 is off what is happening is that the D_B is forward biased And since these two windings are wound on the same core, so using the first winding, the core onto which this first winding is wound, the core will get energized and using the second winding, it will get de-energized and coming back to its original value to again start off in the next cycle or have some average value which keeps on growing and then falling back to the zero point. So this is forward biased and we can say that core is de-energized as the flux in the core comes back or falling down because of this as this will be feeding the power into the load at that point

What voltage we are applying? If you look very carefully during this time, the voltage across this inductor, if I take this as $n:1$, the voltage across this inductor is nothing but equal to, here we are applying the V_0 voltage. So, here if we take down to the primary side, the v_L voltage applied onto this core or onto this winding is

$$v_L = -n \times v_0.$$

Why we have taken n ? because everything we are writing down with respect to the primary.

So, because of this negative voltage applied across this inductor, the flux in the inductor will get decays down or comes back, the inductor current will have the negative slope. Now, because of these two things, what happens is that we can then apply volt second balance in half line cycle. Why I am saying half line cycle? Because this wheel which is there will have the variation nothing but rectified DC which actually varies in half the line cycle.

So, if you take this one this thing from here to here it is T which is nothing but $1/f_s$ and in half the line cycle it actually repeats itself. So, in half line cycle, if you do, we can write

$$\frac{1}{T/2} \int_0^{T/2} \left[(d(t)T_s |v_s| + [(1 - d(t))T_s - n \times v_0] \right] dt = 0$$

You have applied actually here again. If I am writing this T_s , T_s is nothing but $1/f_{sw}$ corresponds to the switching period. So, this volt second balance, if you are doing this and during this time, we are having, if you see previously, it was nothing but $|v_s|$.

So, we can write down

$$d(t)T_s |v_s| - nV_0(1 - d(t))T_s = 0$$

$$|v_s|.d(t) = nV_0(1 - d(t))T_s$$

$$|v_s| \cdot d(t) + nV_0 \cdot dl(t) = nV_0$$

$$d(t) = \frac{nV_0}{|v_s| + nV_0} d(t) = \frac{1}{1 + \frac{|v_s|}{nV_0}}$$

$$d(t) = \frac{1}{1 + \frac{|v_{s,pk} \sin \omega t|}{nV_0}}$$

Now this is the duty ratio of this switch S1 which has to be vary in this manner then only we can ensure that output voltage is having the constant DC voltage as here input we have the rectified DC and output we are getting the pure DC which is nothing but equal to V_0 obviously over which you have you know actually you have something like if you draw we have this V_0 this one over which we have second line harmonics voltage coming over here like this second line harmonic voltage I mean the second line harmonic ripple riding over the capacitor so now from this rectified voltage which is going between 0 to $v_{s,pk}$ from here till this point we are getting just by ensuring that this S1 switches in with a duty ratio that means a fraction of the period in the switching period by this particular variation now if we try to see this particular duty ratio we vary we get the constant output voltage now to ensure the unity power factor current drawn from the source one simpler method we can do is we can opt for DCM operation of fly back based PFCs converter.

So, in this case, let us see what is the discontinuous operation of a fly back-based PFCs converter. So, in this, let us try to draw the inductor current. So, this is T, this is $i_L(t)$. Now, this $i_L(t)$ is something referred to the primary side, which means you can say that it is here I am drawing $i_L(t)$. Now, if you draw $i_L(t)$, since in the in the DTs period, it is applied. You are having the voltage, a positive voltage modulus v_s , and since it is obviously a positive quantity, what we see is that we have a rising slope which goes up to here and which has the slope equal to $|v_s|/L$. During the discharging period, or during the current negative slope period, it happens when we have $(1 - D)T_s$ phase where $-n \times V_0$ voltage is applied across the secondary winding of the inductor.

So, we can write down the i_L , or you can say that $i_L(t)$, or you can say the $i_{L,sec}$ secondary.

Let us define this. This is nothing but $i_{L,sec}$. So, we can write $i_{L,sec}$ as starting from here, will be

starting from here, and then it will have a current which comes down here. Then again, after a certain point, my current will again start from here, come back, and then here my i_s will go down. and then will be zero for some time, and again the next ts will start. So, this period is nothing but the ts period, and this period is nothing but the DTs period. Here, the peak will be, let's say, the peak goes up to here, up to i_{pk} .

So, here it is $n \times i_p$ because this is referred to the secondary side, and the slope will be falling where the slope is nothing but equal to minus $- n \times V_0/L$, or you can say $- V_0/ L$, not $n \times v_0$, just $- V_0/ L$, and this peak is nothing but $n \times i_p$. Now, this period from where to where the D_B is in conduction, we will define this as $d_2(t)$, and we know that we can write $d_2(t)$, is.

$$d_2(t) < 1 - d(t),$$

So, we have $d(t)$, and then $d_2(t)$, and then we have some portion where neither the D_B nor the S1 switch is on, and that's when the current through the inductor is 0. That's when it is called discontinuous conduction mode or discontinuous operation. Now, if you look very carefully, if we try to derive during this point, we can try to derive. So, we can write during $d(t)$ Ts period slope is $|v_s|/L$. So we can write

$$|v_s(t)| = \frac{LI_p}{d(t)T_s}$$

$$I_p = \frac{|v_s(t)d(t)T_s}{L}$$

I_p varies with $|v_s(t)|$

$$\langle i_L \rangle_{T_s} = \frac{1}{T_s} \times \frac{1}{2} \times \frac{|v_s(t)d(t)T_s}{L} \times d(t)T_s$$

$$\langle i_L \rangle_{T_s} = \frac{|v_s(t)|}{R_e}$$

$$R_e = \frac{2L}{d^2(t)T_s}$$

(1)

$$P_o = \frac{V_o^2}{R_L}$$

$$P_{in} = \frac{v_{spk}^2}{2R_L}$$

Assume, the lossless converter $P_o = P_{in}$

$$\frac{R_L}{R_e} = \frac{2V_o^2}{v_{spk}^2}$$

(2)

From (1) & (2)

$$\frac{R_L T_s d^2(t)}{2L} = \frac{2V_o^2}{v_{spk}^2}$$

$$d^2(t) = \frac{4V_o^2 L}{v_{spk}^2 R_L T_s}$$

$$d(t) = \sqrt{\frac{4V_o^2 L}{v_{spk}^2 R_L T_s}}$$

$$d(t) = \frac{2V_o}{v_{spk}} \sqrt{\frac{L}{R_L T_s}} \quad (3)$$

In worst case scenario

$$d(t) = \frac{1}{1 + \frac{v_{spk}}{n v_o}} \quad (4)$$

Substitute (4) in (3)

$$\frac{1}{1 + \frac{v_{spk}}{n v_o}} = \frac{2V_o}{v_{spk}} \sqrt{\frac{L}{R_L T_s}}$$

$$L = \frac{n^2 R_L T_s}{4 \left(1 + \frac{v_{s,pk}}{n v_0}\right)^2} \Rightarrow L_{critical}$$

$L < L_{critical} \Rightarrow$ to ensure to DCM operation, $L > L_{critical} \Rightarrow$ to ensure to CCM operation,

$$L_{critical} = \frac{n^2 R_L T_s}{4 \left(1 + \frac{v_{s,pk}}{n v_0}\right)^2}$$

$L < L_{critical} \Rightarrow$ to ensure to DCM operation, if we can ensure, the 'L' value to be smaller than the minimum $L_{critical}$ value, then we can always ensure the DCM operation. $L_{critical,min} \Rightarrow R_L$ is min & $v_{s,pk}$ is at min, R_L means full load power. $L_{critical,min}$ has to be calculated for peak power demand and at minimum input peak voltage. $L < L_{critical} \Rightarrow$ to ensure to DCM operation not at the maximum value of v_s has to be at minimum value minimum value so the $L_{critical}$ in order to have the $L_{critical}$ to be minimum R_L has to be minimum as and $v_{s,pk}$ has to be minimum and $L_{critical}$ minimum has to be calculated for peak power demand and at the minimum value of minimum value of input peak voltage and that's when if you select 'L' should be less than $L_{critical}$ minimal minimum, then it is ensured DCM is ensured and why we need DCM because we need DCM because once we have a DCM operation then we can ensure that the diode full bridge diode converter sees the purely resistive load and that's when they have the purely resistive load you will draw the unity power factor current from the source advantage what you will get is you have the isolation, isolation is incorporated and you have the voltage follower mode. However, this particular converter can be used for low power applications. This generally for high power application, the size of the coupled inductor will be huge. So, that is why this is limited to the lower power level.

Now, if you look very carefully, the flyback converter is the derivative of the buck-boost converter. So, we can also have diode bridge rectifier. followed by a this is S1 switch and this is the inductor so on the other side if you let's say this is source So, if you see when switch S1 is on the current will be going in this way since inductor current cannot I dropped this one I dropped suddenly. So, we have to ensure that the other side will be drawn.

So, the other side will be there in such a manner that we have the load R_L and we have the operator connected like this not plus minus reverse way around. minus plus V_o and you have the capacitance c now if you look very carefully this particular circuit will be there and this is a circuit D_B this is v_s equal to $v_{s,PK} \sin \omega t$ and this is 'L' inductor which I am talking about so this converter can also be there and here again one can ensure the dcm operation of this inductor and thus this converter can be operated in a voltage follower mode because the effective impedance looking from this side effective input impedance of this buck boost converter buck-boost converter will be input effective impedance will be a resistive and thus the power factor current will be drawn from the source so we can say that buck-boost or flyback converter operated in DCM has the the resistance as resistive effective input impedance and thus the current drawn from the source

will be having sinusoidal variation. So, thus if we can ensure that the buck-boost converter or flyback converter operated in a DCM mode, then we can ensure that we have the sinusoidal current drawn from the source. Obviously, I mean the average inductor current in a switching period is having the sinusoidal variation over the line cycle and at the same time at the peak of the inductor current is also varying sinusoidal in nature. So, this is the way we can obtain the power factor correction converter in case of single phase or in case of when we have a single-phase supply we can either have the boost PFCs based power factor correction converter or we can have the bridgeless based PFCs

We can also have some variation of the bridgeless PFCs but most commonly used are the totem pole based PFCs then we can operate them either in a ccm mode or in a dcm mode in dcm mode the implementation perspective is I mean from the implementation perspective it is very simpler I mean when when it is in DCM mode we can ensure the voltage following characteristic similarly we can also have the buck-boost-based PFCs or flyback-based PFCs converter. By ensuring the DCM operation of the buck-boost converter or flyback converter, we can ensure the unity power factor current drawn from the source, along with maintaining a constant voltage at the output. So, that's what we have studied in some previous 10 to 12 lectures. We will carry forward our discussion, like we will see how the converters are there in case of three-phase systems. We will start our discussions related to that from the next lecture. Thank you for patiently listening to this particular lecture.