CHARGING INFRASTRUCTURE

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Week-04

Lecture-16

Lec 16: Closed Loop Control of Single-phase Boost PFC Converter-IV

Hello everyone welcome to this lecture number 16 of the NPTEL lecture series on charging infrastructure and we will continue our discussion on the closed loop control of a single phase boost PFC converter in the previous lectures we have understood that the boost PFC converter is operated to perform primary two function one is obviously maintaining the or regulating the output voltage at its required value depending upon whatever the reference value given from here then along with that the converter need to be operated in such a manner that The average current flowing through the inductor must be following the modulo single wt pattern and thus in that way we can ensure that the current drawn from the AC input is of the form of unity power factor. That means there is no phase angle between the input AC voltage and the input current drawn from the source.

Now in doing so we understood that since there are two control objectives so we have two control loops one is the inner current loop and the other one is the outer voltage loop. In order to obtain this current controller the first and foremost thing is we have to obtain the Gi(s) and since we have to obtain the Gi(s) we have actually did the small signal modeling of the boost PFC converter and we obtain Gi(s) which is ,

$$G_i(s) = \frac{i_L(s)}{d(s)}$$

and we did a small signal analysis and we obtained that this is the transfer function of Gi(s) now we know our Gi(s) . Now the pending things are 'ki' and the gain 'ki' and the next transfer function which is Gv(s) which is nothing but the transfer function between Vo(s) and the iL(s) or which is ,

$$G_v(s) = \frac{v_c(s)}{i_L(s)}$$

So, let us try to derive the Gv(s) now while calculating the Gv(s), let us we do power balance. Let us do the power balance now what is power balance, what we are doing is we are doing the input power is nothing but equal to the output power of branch which is coming out so we can write down a simple thing input power which is if this is the Vs,pk and the current drawn is of the unity power factor then this one 'is; is nothing but Is,pk sinwt. So, we can write Vs,pk divided by 2 times Is,pk divided by root 2 and Is,pk divided by root 2 just the value of the current and the voltage.

$$\frac{V_{s,pk}}{2\sqrt{2}} \times \frac{I_{s,pk}}{\sqrt{2}} = V_o$$

Now, this is nothing but equal to Vo I mean Vo voltage across this point multiplied by we can write 'i' Converter we can write. And this will be we can write down that 'i' converter value which is coming over is nothing but Vs, pk, Is,pk divided by 2, Vo this is one condition let us define this as equation number one.

$$i_{cnv} = \frac{V_{s,pk} \times I_{s,pk}}{2v_0} \qquad (1)$$

So this equation we got it from power balance and that implies that if there are some changes i mean we can say that if there is some variation which is occurring over this i converter. We can write down that if we assume that $|v_s|$ small signal is equals to zero that means there is no change in there in the 'vs' voltage that means there is no change in the Vs, pk . Similarly, this we can write down that Vs, pk by 2 Vo this Vo is again Vo is the operating point or the steady state point and this is nothing but we can say that is(s). It is because during close loop control it's the 'is' input current which changes around the operating point to perform control action and this is(s). We can write equal to il(s) as iL is equals to 'is' in the positive half cycle and 'iL' equal to minus 'is' in negative half cycle so magnitude change wise they are the same.

$$\tilde{l}_{conv} = \frac{V_{s,pk}}{2v_0} . \ \tilde{i}_L(s) \qquad (2)$$

So, with this relationship we can say that if there is a small change in ‘iL’ while doing control action it will get reflected in the ‘i’ converter current. Now this we define this as equation number 2 and since we are this ‘i’ converter is coming out of this bridge and it is going into the parallel branch of RL and C. We can define the impedance as 1 by SC so we can write down that our Vo(s) is

$$\tilde{v}_0(s) = \tilde{i}_{conv}(s)\left[\frac{\frac{R_L}{sc}}{R_L+\frac{1}{sc}}\right]$$

and this $\tilde{i}_{conv}(s)$ from equation 2 we put the value of $\tilde{i}_{conv}(s)$, and we get

$$\tilde{v}_0(s) = \tilde{i}_{conv}(s)\left[\frac{R_L}{R_LCS+1}\right]$$

So, $\tilde{v}_0(s)$ we can write

$$\tilde{v}_0(s) = \frac{V_{spk}}{2v_0}.\ \tilde{i}_L(s)\left[\frac{R_L}{R_LCS+1}\right]$$

Then,

$$\frac{\tilde{v}_0(s)}{\tilde{i}_L(s)} = \frac{V_{spk}}{2v_0}\left[\frac{R_L}{R_LCS+1}\right]$$

So, again if you see this thing these are I mean if we assume that there is a very small change in the iL(s) current. So, we can also take the small signal value same as this one. There is a small change in the ‘i’ converter and this small change in ‘i’ converter will also lead to a small change in the output voltage. And we can also write in this small variation as well. this is iL tilde and that we can also write in this way.

Here assuming that the assumption is modulus Vs tilde is equals to 0 that means there is no variation in the input voltage.

$$\frac{\tilde{v}_0(s)}{\tilde{i}_L(s)} = \frac{V_{s,pk}}{2v_0}.\frac{R_L}{R_LCS+1}\Big|_{|\tilde{v}_s(s)|=0}$$

Then that particular thing will actually give us the Gv(s) which is nothing but Vs,pk by 2 Vo RL divided by RLCS plus 1.

$$G_i(s) = \frac{V_{s,pk}}{2v_0} \cdot \frac{R_L}{R_L CS+1}$$

So we have come across the Gv value as well. So in the transfer function block, if you see the transfer function block, the entire transfer function block, we have now Gi value, Gv(s) value. Now what we have to calculate is we have to calculate this Ki value. Now this Ki value is nothing but the gain block which tells that whatever the value is coming over here, how does this value corresponds to duty ratio at that particular point. So that we have to see what is the Ki value we are getting. So we are getting this gain Ki is nothing but equal to the peak value of maximum value of control voltage divided by peak value of input current.

$$ki = \frac{Peak\ value\ of\ control\ voltage}{Peak\ value\ of\ input\ current}$$

That means this control voltage is actually give you the representation of duty ratio d and if there is a maximum duty then what corresponds to that maximum duty in the input current what you can say it has been translated so that is what we have to understand now why i have written control voltage so if you see in this particular converter We have already seen the closed loop control diagram of block of this particular converter how it looks like.

Let me recall that particular control block diagram which we studied in some two or three lectures back. So if you recall the block diagram what we have studied in some previous lectures , where we were sensing the output voltage using a voltage sensor and feeding it back into the voltage loop. And we are sensing the current going through the average current which is going through the inductor and we are feeding it into the current loop. In that case we have seen that if we look very carefully we have this modulator block. That means whatever the duty ratio which I am getting this will corresponds to the modulator block.

Now what is a modulator block? Let us see how the modulator block look like. So if we look very carefully in this particular converter structure. So how this particular duty information gets reflected? into the turn on and turn off time of this S1 and S2 basically how it will get translated into the PWM of S1 and S2 which is going into the gate driver of S1 and S2 switches to turn on and turn off the switches accordingly so how this pulse width modulated signal is formed. So, let us try to understand a simple modulator block how the modulator block look like one of the simplest ways to modulate that converter. Now why we have to do modulation we have to do modulation just to make sure we can able to actually vary the voltage at the output of this half bridge in such a manner that on an average sense we are getting the required voltage what we wanted. So now we need to do modulation, so here what we are trying to do is we are trying to keep the frequency constant so switching frequency is kept constant which is nothing but fsw is kept constant. If my fsw is kept constant and then my duty ratio is getting generated, so this duty ratio will be somewhere between let's say 0 and 1. So, how using modulator block it will be generated so most commonly used way is we can have a carrier, so we can have a carrier now what is a carrier carrier signal so we can have a carrier signal this carrier signal is nothing but it could be either triangular carrier or ramp carrier ramp going in up direction zero to certain maximum value is going from zero. To that maximum value in triangle it is going from minimum value to maximum value and then coming back to the minimum value in ramp it is going from minimum value to maximum value and so it is like triangle, if we see this will be a triangular carrier signal and this will be the ramp and then again it will start like this, this is the triangular carrier this is the ramp carrier now in this if this is a ramp kind of thing or triangular kind of thing let me also draw the carrier in much better i mean the same uniform carrier let me draw that now in this one in triangular we have both up down

I mean we have a counter going up and counter going down in ramp we have a counter just going up and then when it reaches its maximum value it form that maximum value it will be converted directly into a value equal to the minimum value and then again it will rise 1 by 1 it will rise so now what happens there is a duty which is coming, so that duty is varying between 0 and 1 which is the output of this this duty will be just you can say, it will be just compared with the either this carrier or this carrier just the value comparison is happening and assume if this any of the carrier it could be any of the letters for simplicity. Let us take the ramp carrier it is going between assume it is going between 0 to Obviously, since it is kept inside the microcontroller, it will be going between 0 to the maximum control voltage it can go. So, inside the modulator block, this duty ratio d which is varying between 0 and 1 is compared with the carrier which is varying between 0 and Vc. So the duty ratio value has to be converted proportionally to the control voltage value, which indicates that when d equal to 0, it corresponds to 0 point in the carrier and when d equal to 1, it corresponds to the Vc point in the carrier.

So if assume our Vc is equals to 1, then my duty has to be between 0 and 1. And this will get compared. So let us see if this is your ramp signal. Now this RAM signal is getting compared with duty ratio d and there will be let us say this is your carrier let us say Vc. So Vc is actually compared between duty ratio d, I mean d signal or you can say this d signal you can say that it is a modulating signal with slow varying modulating signal and it is a high frequency carrier signal.

So, one important thing is the carrier frequency, which is the fc, corresponds to the time period when the carrier goes from the minimum value to the maximum value and then comes back to the minimum value. That means the frequency with which it repeats, the carrier frequency, has to be again very, very much greater than the fs value $f_c \gg f_s$. f_s is nothing but the line frequency. Thus, we can make sure that f_c, or the carrier frequency, is very, very much greater than the frequency of this duty ratio varying. And this particular thing, we can name it as the modulating signal. So, it is a slow-varying modulating signal. That means $f_c \gg f_m$, where f_m is the frequency of the modulating signal. Now, this modulating signal, which is there, is always getting compared with the v_c. In our case, the modulating signal is nothing but the duty which is coming over here.

So, let us compare this one. So, we can say that if my carrier, or we can simply say this thing is the carrier is greater than the modulating signal, then PWM is equal to 1, or PWM of S1 is equal to 1. If it is the other way around, if the carrier is less than the modulating, then it is PWM of S1 is equal to 0. This PWM of S1.

We can see PWM S1 is equal to 0. PWM S1 is equal to 0. The same PWM S2 is generated by the NOT gate. So, if you see very carefully, since my carrier frequency is kept constant.

I am making the carrier frequency kept constant and modulating waveform is only changing. So, we can say that at this point the curve, let us say at this point my modulating wave is greater than the carrier wave. So, my PWM is 0. PWM of S1 is 0 and at that point beyond this particular point the carrier becomes greater than the modulating that's when my S1 PWM become 1 and then again at this point since after reaching to a maximum value , it falls to 0 that value it falls to 0, so that means our this value is again goes to 0 and so on. So this is my PWM of S1 which is coming out of this modulator block.

So this is nothing but we are doing a simple comparison the whatever duty ratio is there is getting compared with the carrier waveform. It could be either RAM carrier or triangular carrier. In this case we can take RAM carrier for simplicity, because it is just a DC-DC converter. And this we have to make sure that this modulating wave or you can say that which is nothing but a duty 'd' this duty 'd' must vary between 0. In this case let us take zero voltage minimum value as zero voltage and maximum voltage of this RAM which is nothing but we have defined as a v_c or we can say that control voltage that so this duty ratio or this duty which is getting generated must be between zero and the maximum control voltage or in simpler word. We can check if this is 0 and if this is equal to 1volt then it must goes between 0 and 1.

So, from here only we can take the ki the peak value of control voltage which is nothing but this maximum peak of the carrier which can go it could be either 1 or it could be either 3.3 volt it could be either 5 volt if it is written in a digital domain then it could be just the maximum value of we can define one counter which goes between 0 and the maximum value and that could be the maximum value. And this duty whatever is there modulating wave in the digital domain will be some fraction of that maximum counter value and that we have to make sure that that duty is varying between 0 and that maximum value of counter value. So, that counter value we can define and when the duty reaches to that maximum counter value what will be my current in the circuit it corresponds to the maximum current. So, we have to define the Ki in this manner. So, peak value of control voltage which corresponds to the peak value of duty ratio going between 0 and 1 and this one is again dependent upon what will be the peak value of current in the input side.

So, with this, we have defined our Ki value and Gv(s), and that is when we were able to close down our circuit. The entire closed-loop control—now, if you look very particularly at this particular closed-loop control—we have obtained the Gi(s), we have obtained the Gv(s), and we have obtained the Ki(s). Now, the next criteria we have to address is: what will be the criteria to select this current controller, and what will be the criteria for selecting the voltage controller? Let us see the two-loop structure we have already understood. So, in this, we have V0, we have the inner loop—the inner current loop—and the outer voltage loop. Now, if you look very carefully, this inner current loop—whatever the inner current loop is—it has to be a faster loop. First, this inner current loop—the inner current loop—is faster than the outer voltage loop. Now, why are we saying this? It also makes sense because the output voltage is nothing but the DC voltage, and the change in the DC voltage is not too much. This change in the DC voltage must dictate this current reference of the inner current loop, and that current loop must respond to that change in the reference. So, that means this loop has to be faster than this outer voltage loop. That's why this inner current loop is faster. Now, let us just draw the inner current loop and see—I mean, what are the criteria we can have—if we see just the inner current loop. Now, if we see this inner current loop, what we have is we have iLref(s). And this is feedback we are getting. This is the current controller going into Ki, Gi(s), iL. This gets closed. Now, if we just look into this particular current loop, we know that this will have the $|\sin sin\ \omega t\ |$ variation. That means this is a 100 Hz varying signal—a 100 Hz varying signal or, in simple terms, or in the most generalized manner, we can say that it is the $2f_s$ varying signal. This is a 2 f_s varying signal.

In most generalizers, where f_s is nothing but the line frequency. So, now, what are the—this particular loop must have a very high gain for the $2f_s$ frequency, or you can say the 100 Hz frequency. And at the same time, if you look very carefully, the current waveform—our current waveform—actually looks like, since we are having a constant frequency. This thing—our current, iL current—will look like this. This is the average iL current in a switching cycle.

But the actual current will be something like going like this, going like this. The actual current is actually be drawn in the green color that kind of current that means this particular current is having a 100Hz ripple. I mean basically the frequency component the fundamental frequency component is 100 Hz. and over that there is a high frequency ripple and that high frequency if you see since we are doing a constant frequency constant frequency operation this particular is nothing but T_s which is nothing but $1/f_{sw}$ so that means in this particular current if you do the harmonic analysis it will have the 100 hertz component and along with that we will also have the component in the switching frequency Other than that below that there is no there is no frequency coming. Because I mean if you do the fourier analysis of that it will be just having the fundamental then fundamental then first harmonic of this f_{sw} then third harmonics of f_{sw} fifth harmonic of f_{sw} and so on.

Similarly if you see there is no low order harmonics which are present only the 100 hertz component 100 hertz frequency is there and then after that there is a high frequency ripple which is at f_{sw} frequency. So, thus if we look very carefully see our objective is to make sure that our closed loop control must this is my il average so our aim is we should make sure that this iL average current which is shown in the red color which is having a variation shown in the red color we should be actually be tracking that iL average and this ripple over that iL average will be still be there so our aim is to control this iL average we our aim is not to control this ripple I mean ripple which is there over the iL average so thus we should make sure that the controller is designed in such a manner that it should be able to track this il average variation which is nothing but having the 2fs variation and at the same time it should be in a position to reject that high frequency ripple or high frequency component of current which is present in this in this actual iL current. So, the first objective is we must make sure that the current controller must be designed to track the $2f_s$ component , and how we can make sure that thing happen just in a negative feedback system we can make sure that the feedback follows the reference when the gain at that particular frequency is enormously high or is infinity how we can say that we can just take a simple closed loop system having some reference let's say controller is defined as the c of C(s) and going to the plant P(s) this is the output which is actually feeding back into the i mean which is actually send in the negative feedback form. Now if we see this particular closed loop control where our objective is to make sure the feedback whatever is coming is following the reference that means the error at this point is equals to 0. What it indicates that the output is following the reference. So we can write down in the closed loop control we can write down as:

$$\frac{0/p}{f} = \frac{C(s)P(s)}{1+C(s)P(s)}$$

Now if my C(s).P(s) >> 1, then I can say that

$$\frac{0/p}{f} = \frac{C(s)P(s)}{C(s)P(s)} = 1$$

and that implies,

$$\frac{0}{p} = f$$

So, what it indicates if there is a variation in the reference then that frequency of that variation if you want to track that variation then you must make sure at that frequency of that variation the gain provided by the multiplication of C(s) and P(s) that means the gain of the open loop transfer function, which if you open this feedback then the open loop transfer function is nothing but C(s) and P(s). Then the gain of that open loop transfer function must be infinity or must be very very much larger than the value 1 and that is when we can make sure that the output is following the reference. So, if the reference is having let us say 100 hertz ripple then I must make sure the gain of the C of the product of C(s) and P(s) must be infinite or must be very large such that my output will also be having that same 100 Hz variation or you can say that output will be closely following that reference.

This is a very commonly used concept in the closed loop, I mean the closed loop control of systems where if you make sure that the gain of open loop transfer function is enormously high, then we are ensuring that the output is following the reference. And if that reference has certain frequency component, and if i want the output should track that particular frequency component then i must make sure that at that frequency the open loop transfer function must be having a very high value of gain. So, thus the controller must be designed to track the 2fs component what it indicates the gain of open loop transfer function must be very high at 2fs frequency. Let's say if it is a fs is 50Hz then the gain at 100 Hz must be very large or the gain of the open what is open loop gain the expected current going to multiplied by ki and multiplied by Gi(s) if they must have a very high gain at 100 Hz. So, then if you make sure that they have they have a very high gain at 100 Hz then we can make sure that whatever the iL reference which is nothing but the average variation of the inductor current is there then the actual inductor current will be following that reference. So, with this the first criteria by which a current controller can be designed so one can choose one kind of current control and then do the body plot and then can see what is the gain at 2fs frequency and they must select that control in such a manner that you will have a very high gain at 100 or 2fs frequency. Now the second thing one can do is see we know that along with this 100 Hz variation or you can say 2fs variation in the iL average there is also a current ripple and that current ripple has the frequency which is nothing but equal to switching frequency or fsw so thus our controller is designed such a manner that the bandwidth of this this current loop the bandwidth of current loop is must be less than less than f switching frequency now what is bandwidth the bandwidth you can say that in a simpler manner it's the is the frequency at which the gain plot of the open loop transfer process crosses the 0 dB line or you can say that the 0 dB line is nothing but the place where you are you are going from the gain to the attenuation. So thus, we if we make sure that bandwidth is very very much smaller than switching frequency. Generally we assume that bandwidth of current loop if it is f switching by 10 times let's say if your switching frequency is 20 kHz then you can select the bandwidth as 2 kHz if your switching frequency is 70 kHz you can choose bandwidth somewhere around 6 to 7 kHz then at that time you are 100 percent making sure that there is a good attenuation attenuation at, I mean you can say the good attenuation at, good amount of attenuation at

Now it is important because we do not want to amplify the switching frequency ripple current due to the control action. That means we do not want to provide any gain at f_{Sw} frequency. The ripple will be there due to circuit operation but we do not want to amplify it further due to control action. we only wants to track the average variation of inductor current in a switching cycle which is varying with two fs frequency and thus we must make sure that we are providing a good amount of attenuation at the f switching frequency if we following these two criteria one can design one can choose the current controller it could be a conventional pi controller it could be p controller it i mean proportional controller or it could be a proportional integrator controller or it could be a type two controller i mean higher order controllers one can choose but the controller whatever is is selected or the transfer function of the control whatever is selected one must has to do need to do the open loop transfer function analysis and they must make sure that they must plot the body body plot and must make sure that these two conditions is following that means there is a good gain at gain of that open loop transfer function at 2fs frequency and there is a good amount of attenuation at at switching frequency. And then third point you can ensure that you have a sufficient phase margin and gain margin with the system. Generally the phase margin if it is between 35 to 60 degrees it is considered as good and that's when we can make sure that there is a good stability also is there in our closed loop transfer function so this is following these three things one can easily select the current controller transfer function. Again one need to one need to do the body plot analysis and need to see how the transfer function look like. Similarly if you look very carefully now we have found out the current loop controller now once we found out the inner current loop controller we can easily find the closed loop closed loop transfer function of this particular inner current loop let us define as the Gccl(s) which is nothing but the closed loop transfer function of this particular inner current loop let us define this current controller Cc (s).

so we can write down

$$G_{ccl}(s) = \frac{C_c(s)\cdot k_i\cdot G_i(s)}{1+C_c(s)\cdot k_i\cdot G_i(s)}$$

the $G_{ccl}(s)$ is nothing but $C_c(s)$ which is a current controller multiplied by k_i multiplied by $G_i(s)$ divided by 1 plus $C_c(s)$ k_i multiplied by $G_i(s)$ and then you can define the new transfer function nothing much so first is we have to select the current controller parameters and once it is defined one can then choose the voltage controller , as it says $C_v(s)$ and this is again if you look carefully it is going through the saturation block multiplication block $|\sin sin\ \omega t\ |$ and then finally we will write $G_{ccl}(s)$ which is a closed loop i mean closed loop transfer function of the inner current loop then following with Gv(s) then the output and that will be read it back to the loop. Now if we look this particular this particular loop now we have obtained this particular transfer function because we have already understood how our current control looks like so we can easily define the closed loop current transfer function and then now using this two transfer function we can have this particular loop where we can i mean this things we can neglect and what we have is using this voltage controller loop we have the open loop transfer function is nothing but again for voltage loop outer voltage loop is nothing but your $C_v(s)$ multiplied by $G_{ccl}(s)$ multiplied by Gv(s)

$$\text{Outer loop T.F for voltage loop} = C_v(s).\,G_{ccl}(s).\ \ G_v(s)$$

Similarly, if you see in this thing, our open loop transfer function, if we define the Cc(s), then here the open loop transfer function is nothing but Cc(s), multiplied by Ki multiplied by Gi(s). This is the open loop transfer function of inner current loop.

$$\text{Open loop T.F of inner current loop} = \ C_c(s).\,k_i(s).\ \ G_i(s)$$

So, you one so this is the transfer function one need to do the bode plot and then make sure the Cc(s), is such that these three conditions are met and that's when you can choose the current controller. Similarly, in the voltage loop you can define open loop transfer function for voltage loop and then there are some criterias you can follow, so the first criteria if we look very carefully our output voltage is kind of a dc. So we must make sure that we have this open loop transfer function must be having a very high gain at the dc at the dc that means your 's' = 0 , so the first and foremost thing is the very high gain at s= 0 or very high dc gain must be there. Second since we we have this dc quantity to be traced to be to be actually we we wanted to have the tracing of that so we must make sure the bandwidth of voltage loop must be between if you can make somewhere between i mean you can be very much nearer to s equal to zero you can have 20 to 40 Hz you can have and so that you do not be stressing too much on your controller you do not have to oversize your controller as well and that's when you can define the bandwidth of voltage loop using these two things criteria for using these two things you can calculate the voltage controller. So, thus what we have seen some of the criteria to calculate the or to come up with the voltage controller and also to come up with the current controller, and here we must make sure that it has in voltage controller we must make sure the voltage controller should be such that it has a very high gain at s=0 and having a bandwidth which is near to 0 which is you can take 20 to 40Hz. Because we do not want that our controller should be unnecessary having a very high values or you can say that optimally sizing your controller one can do. Similarly, in case of inner current loop the inner current controller must be selected in such a manner that the open loop transfer function must have a very high gain at twice the line frequency that means 100 Hz if it is line frequency is 50 Hz and along with that they should have a good attenuation at switching frequencies just to avoid the amplification of the ripple present in the actual inductor current. We must provide a bandwidth somewhere near to one tenth of switching frequency. So that will give a very good attenuation to the ripple at the high frequency which is at the switching frequency and then the loop must have since this loop is quite faster loop. So the stability of the loop is also need to be ensured so we must have a sufficient phase margin and gain margin while designing this current controller. Similarly in case of the i mean once we define the current controller one can easily calculate the voltage control. So with this we can easily able to design or do the closed loop control and here we are just trying to control the average inductor current and we are actually ensure that the current is following the variation which is the $|\sin sin\, \omega t\, |$ the inductor current I mean on in average sense is following the modulus of single wt variation and thus our current drawn from the source is having a unity power factor current.

So, thus we have seen how we can do the average current control of a boost PFC operated in inner i mean if you see the current inductor current it is a continuous inductor current so we can say that it is in the continuous conduction mode now apart from this control method we also have other controls methods as well but this is the most simplest and best way one can understand this thing where we have kept our switching frequency constant along with that so we have seen, so other control methods. Again in this particular control method what we have discussed. We have kept our switching frequency to be constant.

The switching frequency is constant. That means sometimes it is also called as the constant frequency control. We are only changing the pulse width, or the duty ratio of the switch S1 and S2 and accordingly varying the on an average length varying the voltage at the output of the half bridge and thus in a way controlling the inductor current. So the other control methods are first one is peak current control in this what you are trying to do is you are actually defining the average variation of current to be like this and you are making sure that the ripple what you are getting is such that it the moment the ripple hits the the peak value of the ripple hits the that this particular variation or the flap variation if i define this as iL. And the moment it reaches, it goes down. The moment it reaches, it goes down. The moment it hits that peak variation of the current, it goes to the current goes down. So, like this, something like this shape we can imagine. So, this is nothing but a kind of peak current control.

However, in this case, if we see in this case, this is actually the variable frequency case you can say because in this since our input voltage is varying and we are keeping our peak to be same as that shown over here further we are also keeping our turn off time constant while the turn on time is varying over the line cycle as the peak value of current need to be controlled in a manner shown here. Turn on time is constant so thus the frequency has to vary. Then the another method is variable hysteresis control in that what you will do is you will define hysteresis band like this this is variable band will provide and you are now making sure that the actual current actual iL current.

It will be going the moment it hits the top band. The S2 is on, and it comes down. Then, the moment it is at the bottom band, S1 is on, and it goes up. Then it comes down, goes up, comes down, goes up, comes down, goes up, comes down, goes up, comes down. So, the current is within the band, something like this. And thus, you can ensure that the current has the average variation, which is of $|\omega t|$, and has the ripple over it. Thus, this is a kind of variable because the band is varying. Over the line cycle, this is another method one can employ while doing closed-loop control. But with average current control, or you can say constant frequency control with average current control, you can easily understand the concepts. So, with this, we end our discussion on the closed-loop control of the PFC converter. In the next class or lecture, we will discuss topics like some variations of this kind of converter and move forward with our discussions. Thank you.