CHARGING INFRASTRUCTURE

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Week-03

Lecture-13

Lec 13: Closed Loop Control of Single-phase Boost PFC Converter

Hello everyone welcome to this lecture number 13 of NPTEL lecture series on charge infrastructure in this particular lecture we will talk about closed loop control of single phase boost PFC converter and in previous two three lectures we were discussing about how one can size And one can decide on this sizing of different components and can select components with required ratings and thus can able to physically realize this single phase boost PFC converter in hardware. So, over these 2-3 lectures, we have derived some of the important aspects. First, we have seen, we have derived the duty ratio, which is nothing but the fraction of the time of switching period during which this switch S1 is on. That we come to conclusion that is nothing but 1 minus modulus of vs sin omega t divided by V naught.

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

And then similarly, we have also calculated the inductance value, which is nothing but V naught divided by 4 ΔL,max multiplied f switching frequency. Similarly, we have also defined or calculated the capacitance value. And we have also seen that this capacitance also has the second line harmonics, second line harmonic frequency component. in the voltage in the capacitor voltage which it is there.

Similarly, the capacitance value,

$$C = \frac{P_L}{\left(2\pi fs.\Delta v_0.Vo\right)}$$

So, this second line harmonic component is one of the reasons why the capacitance size is enormously very high and this is one of the problems in single phase AC to DC converter where the converter is operated in such a manner that the unity power factor current is drawn and it is maintaining a fixed output voltage V naught. So, this second line harmonic component or the second line harmonic frequency component is one of the important consideration which will be there on to this capacitance. Then we went ahead and derived the RMS current expressions for S1 switch. We have also derived RMS current expression for S2 switch. we have also derived the average current which will be flowing through the S2 so similarly one can also derive the average current which will be flowing through this S1 switch nothing but Iavg, S1 is 1 divided by T divided by 2, 0 to T divided by 2 integrated is of t dt. One can also calculate the average current through S1 as well.

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

We have also seen the voltage ratings. The ratings of S1 and S2 are nothing but V0, and generally, one has to give a certain safety margin, generally 1.4 times of that voltage, which it has to block whenever the converter is in operation. So, the voltage blocking of these devices we have seen. So, accordingly, depending upon the voltage rating and the RMS or average current rating, one can choose the appropriate devices which can be used to realize these S1 and S2 switches.

Then, we have also seen the RMS current through the inductor, which we have obtained as Is ,pk divided by the square root of 2, where Is ,pk one can easily calculate using the formula defined. It is assumed that the converter is operating in such a manner that the unity power factor current is being drawn from the AC input source. And going ahead, we have also seen the RMS current which will flow into the capacitor is nothing but the square root of the RMS current of this converter current minus the square of the average current that will flow into this load.

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

We have also seen some of the ratings of these diodes. For selecting these diodes, we have seen that for D1, D2, D3, and D4, the VRRM was nothing but Vs,pk.

$$D_1, D_2, D_3, D_4 \rightarrow V_{RRM} = v_{s,pk}$$

The average forward current we have also seen was nothing but Is,pk divided by π.

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

We have also seen the IRMS was nothing but Is,pk divided by 2 .

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

So, using these ratings, one can also select or choose the required diode, and thus one can easily. Realize this part of the converter, and using the formula we have derived, one can also realize the other key components of this power converter. Now, up till now, we have studied the operation of this converter. We have understood how one can size different components of this converter. Now, the next important part is the closed-loop control.

If we see in closed-loop control, so what are the control objectives we are trying to solve in this particular converter? Using this particular converter, what are the control objectives? So, the control objectives are: the first objective is obviously. Regulating the output voltage at a desired level or at a value which is needed to satisfy the specification of this particular stage of the power converter. So, the first control objective is the regulation or controlling of output. DC voltage at its desired value. Now, we have seen that fundamentally, that desired value has to be greater than. vs,peak. So, if the specification is given as the output voltage needs to be maintained at 400, then the closed-loop control or the switches have to be controlled in such a manner that you will obtain that 400 V, whatever is the required or the desired value. One needs to have a second control objective, which is, along with maintaining or regulating the output voltage, another important thing, which is the most critical part for this single-phase boost PFC converter, is the unity power factor current drawn from the source.

So, thus the second control objective whatever the things you are controlling you must make sure that the unity power factor current is being drawn from the input ac source or from the grid you can say it is after the voltage control this is the second most important requirement of of the

operation of this converter Now, how you can maintain these two things see one cannot change this diode conduction period it depends upon whenever it is forward wire it will be conducted whenever it is reverse wire it will not be in conduction. So, thus the we do not have control we do not have any control when the diodes are turning on and turning off. So, this we do not have control thus L and C are the passive component which are being used.

the only thing which are available with us which can be controlled are the switching time of this switch S1 and S2 within a switching period so the only control variable or the or you can say the things one can change is are the fraction of the time during which this S1 switch and S2 switch is on in a switching period that means in how much time for how much time this switch has to be on and how much time this switch has to be on in the Ts period where Ts is nothing but 1 divided by fsw.

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

where, fsw is very very much greater than our line frequency generally this fsw will be in tens of kilohertz maybe 10, 20, 30, 60, 70 depends upon the designer's choice. So That's the only thing you can control which is nothing but the switching time for that particular switch S1 and S2 because if we control these voltages then on an average sense we can control the voltages which are applied over here and that's when you can make sure the current drawn is of unity power factor and accordingly we can also control the output voltage one can obtain. So that is why we have this one particular thing is the duty ratio which has to be changed through the closed loop control. Here one assumption is being taken that the switching frequency of half bridge that means f_{sw} is kept constant.

Because if we have varying switching frequency then it will lead to several other problems like emi's different harmonics appear in the supply current operation of converter is completely different and the relationships what we have obtained will not hold true so that's why f switching frequency is kept constant which is at a very very much higher value than fs which is nothing but the line frequency So, now to obtain this to control objective there are several control scheme which have been followed and one of the commonly used control scheme is to control the average is to have the average current control which is nothing but which controls the average

inductor current by appropriately changing the duty ratio of the switches. so let us see how our overall closed loop control will look like so our first requirement is to maintain the constant output voltage or to have the regulated output voltage and that particular output voltage should be at the desired value so we can define the reference voltage which is Vo reference voltage that what voltage one need to have or need to regulate at the output load now that will be nothing but will be compared with the Vo feedback Now we will see how one can generate this Vo feedback.

So that will be generated by sensing this particular Vo. So we have a V naught reference, which will be compared with the V naught feedback, and that will be sent to the controller, which is nothing but the voltage controller. One can use Any kind of controller: it could be a PI controller, a P controller, a proportional controller, a proportional integral controller, or type 2, type 3, or some high-order controllers can also be used. So, this is that particular controller.

We will also see some of the guidelines that can be followed to select this controller in subsequent lectures. So, then the output of the voltage controller is sent to the saturation block. Now, let us understand why we need this saturation block. Now, if you see in this particular arrangement, what we have is we have the reference voltage, which is being defined or which we need to maintain at its output.

Now, we are also comparing it with the feedback. Now, if there is a difference in this quantity—for example, if this is kept at 400 and this is at 350 V—then what it indicates is that the capacitor needs to get charged up, so the current drawn by the capacitor needs to be increased such that this capacitor voltage will rise and reach this Vo reference value. And how can one make sure the capacitor will get charged more? One can ensure that the capacitor will get more charge by increasing this I converter current, and how can one make sure this I converter current will increase? This can be increased by ensuring that more current is drawn from the source. Because one cannot change the source voltage.

One can only change the amount of current which can be drawn from the source. So that means if there is a difference between the required or the reference voltage. And the feedback voltage or the actual voltage. Then that particular thing will give. The indication that whether we have to draw more current from the source or less current from the source.

Now, let us take one more example. For example, if you want to keep this Vo reference at 400 volt and let us say Vo feedback is at 420 V. That means one need to make sure that this capacitor should discharge more and reach to that 400 V mark. Now to do that one need to make sure the energy which is used to charge the capacitor will be should get reduced then only we can make sure the capacitor will be discharging more and that is when the voltage will fall down to 400 V. So, that means how one can make sure the it will be discharge more by making sure this I converter value goes down and how one can make sure this 'i' converter value goes down when this reduction in 'I' converter is getting reflected in this 'is' current and how one make sure this reduction is in current can be ensured by somehow making sure that there is a reduction in this 'iL' current.

So, there are two things if my Vo feedback is greater than Vo reference that means the capacitor needs to discharge and how one can make sure capacitor is discharged by making sure the I converter get reduced because this current which is going into the load one cannot control so one way is to make sure i converter get reduced and how one can make sure 'i' converter is reduced by making sure the il got reduced and once the il is reduced it indicates that my is will get reduced similarly if the V feedback is smaller than Vo reference that means the value at which you want to keep the voltage so in that case the capacitor need to charge which indicates that the 'i' converter need to increase that indicates my iL need to be increased and that indicates that my is current which is withdrawn from the source need to increase. So, what we saw that the difference of this voltages will actually determine magnitude of inductor current in the converter. Because that only you can control by controlling the switches.

And once this gets reflected here, you will see that the reflection will also be there on the 'is' current. So now, this will define the magnitude of that 'iL' average current. Now, that particular thing , I will multiply with the modulus of the unit sine function, or you can say $|\sin \sin \omega t|$, and that will give you nothing but 'iL' or'iL' reference—that will give you the 'iL' reference. Obviously, this will be in the average sense—'iL' average reference, I should say. 'iL' average reference—that averaging is done in a switching cycle.

Now, this'iL' reference will then be compared with the 'iL' feedback. So this defines the magnitude and will be multiplied with the $|\sin \sin \omega t|$.That means now, if you look at this

variation, this reference variation will be of the form. Something like this. And the peak is nothing but defined by this. If I define this as IL,pk, then this will be nothing but my IL,pk.

By IL,pk, because this thing is now multiplied with the $|\sin \sin \omega t|$. Now, to generate this $|\sin \sin \omega t|$, there are single-phase PLLs which are available, or one can also sense the. Grid voltage and then take the modulus of that, do the mathematical operation on that, and then remove the peak value or to obtain $|\sin \sin \omega t|$, and that one can multiply it with this output of the voltage controller. Now, why is this saturation given? Because once you have decided on this particular converter, you know what could be the RMS value of IS1, what could be the RMS value of IS2, what could be the RMS value of the current of the inductor, capacitor, or diodes one can have. And that is when this saturated value or this saturation limit will be determined.

Because you have already selected the components so we need to respect the maximum current ratings of this components and that's when that saturation is needed so one make sure that this controller is tuned or is having such parameters such that control is happening and it is not going and getting saturated so one one can do that exercise while defining the control parameters. So, let us see further let us again go ahead and see the further things now after this il average reference and feedback so this again this reference and feedback now again this will be having one current controller whose work is to make sure that this feedback will be following the reference, and then this current controller. Now if there is a difference between them then this controller will make sure the error goes to 0, I mean this error goes to 0 and how one can make sure this error goes to 0 by making sure this the duty ratio of this these switches S1 and S2 is changed accordingly. So now this will be obviously there will be some gain We will discuss this gain as we go on.

So there will be some gain which will actually convert this output into the duty ratios which is required. So that will define the duty ratio. Let me define that is a duty ratio in terms of 's' (d(s)). And that will go to again the modulator block, modulator block and that will define my PWM of S1 switch and one can take the NOT of that and can define the PWM of S2 switch, you can say this PWM is going to the gate driver of S1 switch and this PWM S2 is going into the gate driver of S2 switch. Accordingly, now one need to use the output voltage sensor so these one can put the voltage sensor and this voltage can be sensed and can be feed back to the

voltage feedback and then this controller will make sure the error over here goes to zero and then this 'iL' feedback, one can put the current sensor here and then take the current sensor feedback and connect to this feedback and then this controller will be making sure that this error which is coming over here is making down to zero.

Now if you look very carefully here we are trying to control the average current which is going through the inductor that is why it is also called as a average current control of boost PFC converter. We are controlling the average current, which is actually following the |sinwt| pattern. So that's why we have multiplied with the |sinwt|. Now, if we see here, this particular part is actually be placed inside the controller. This all things will be kept inside the controller.

So, this is kept inside the microcontroller in the digital domain. One can design and keep it inside modern-day microcontrollers. One can keep and write down the the particular codes for individual blocks, and that is when one can ensure the PWM S1 and S2 is coming out of this controller and going into the gate driver of these switches. Now, here it is not d(s), it will be d, which is going into the modulator. Now, let us see how we can design these controllers, and to design these controllers, one needs to also know what will be the transfer function of the plant you are trying to control.

Because once you know the transfer function of the plant, then only you can be in a position to define the controller parameters so that the response of the plant will follow your desired specifications.

So, let us see how one can write down the closed-loop control in such a form that we can easily analyze it. So, let us write down again the closed-loop control. It is nothing but not reference; the feedback will be coming over here. Then you have a voltage controller that will be going to via a saturation block, will be going to a multiplier, and then that will define the, let us say, Vo (s). The output of the multiplier will be defined as iL (s) , and that will be compared with iL feedback. Here, it will be compared with Vo feedback and given to the current controller, and the output of the current controller will be sent to the gain 'ki', which we have taken. One gain because this gain will be used to convert this particular controller value into the required duty, and that will define the d(s).

Since we are writing this in the S domain, we are writing this system in such a manner that we can use certain control system tools to select these controllers. So, that is why we are defining these parameters, or you can say these particular quantities, in the S domain. So, this is a d(s) which we are getting. Now, what it indicates is that whenever there is a change in the duty ratio, that duty ratio So, we see in this particular converter, whenever there is a sudden change in the duty ratio of switch S1, then the average value of V converter, which is V, changes suddenly.

This will result in the sudden change in the voltage across the inductor and as we know that the current through the inductor will take some time to respond to the sudden change in the voltages applied across it. So, thus the dynamics of this delay in responding to the sudden change in the applied voltages need to be captured in a transfer function and that will be the plant transfer function which will actually capture the way that this particular converter behave once there is a change in the duty ratio. So, we will define a function called Gi of s now this Gi(s) is nothing but iL(s), whenever there is a change in the duty ratio we can define this as small i because that's a that's the moment which we are trying to follow so that 'iL' of s upon d of s that means whenever there is a change in the duty ratio how the that particular change in the duty ratio will get actually propagated, or you can say that how the system will get respond to that change in the duty ratio that means the current through the inductor which will take some time or it will have some dynamics to that sudden change in the duty ratio. So, that will be captured that way it will behave it will be captured in that Gi(s), now that will give you nothing but iL(s) that will be taken feedback to this and it will be compared with iL reference and this output of this if you see this one if there is a change in the inductor current then definitely there will be change in the I converter current and thus there will be change in the current which will flow into the capacitor which will actually lead to the change in the capacitor voltage which the capacitor takes some time to respond to the change and that particular behavior response of that particular capacitor will be captured in the transfer function we define it as a Gv(s) and the output will be nothing but your Vo(s) which will be again feedback into your system where Gv of (s) we can write the output of Vo(s) divided by iL (s). and we know that whatever the Vo(s) is there is nothing but same as that of Vc(s) so what we have what we are trying to do we are trying to see whenever there is a change in the duty ratio how the inductor current will respond to the change in the duty ratio that information has been captured in Gi(s) and then once the inductor current gets changed how the capacitor voltage will respond to the change in the inductor current because

the change in the inductor current will reflected in the i converter current and that will actually be reflected in the current which will be going through the capacitor and that will be actually be reflecting in the voltage of the capacitors and the capacitor resist to that change and take some time or have some dynamics involved in while changing the voltage of the capacitor. So, thus we will capture that dynamics in that particular Gv (s).

So, now our prime objective while doing the closed loop control in order to understand the parameter of this current control and voltage control our prime objective is to make sure that we know this Gi of s which is how the inductor current will respond to that duty ratio change that we should know and with the change in the inductor current how the capacitor voltage will respond to that particular change in the inductor current that we should know so for that transfer functions Gi(s) and Gv(s) need to be known which can be obtained using the small signal modeling and while doing small signal modeling we will follow certain procedures to obtain the small signal model.

So, small signal model so while deriving this small signal model we will first derive the average large signal model obviously using different state equations.

Then we will give a small perturbation to the inputs, such as duty ratio and input voltages, and then observe the response of inductor currents and capacitor voltages to these small perturbations to capture the dynamics. Then we will linearize the state equations around the steady-state point, or around the operating point. This linearization will be done by making certain approximations. Once we linearization it around the operating point, we can then convert the time-domain equations into the S-domain equations, Laplace-domain equations, or frequency-domain equations And that's when we obtain the transfer functions of Gi(s) and Gv(s). We will derive this in the subsequent lectures.

Thank you for patiently listening to this lecture, in which we have seen how one can implement average current control of a single-phase boost PFC converter.