CHARGING INFRASTRUCTURE

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Week-06

Lecture-28

Lec 28: Closed loop control of three-phase AC-DC converter-III

Hello everyone welcome to the lecture number 28 of the mptl lecture series on charging infrastructure in today lecture we will discuss the closed loop control of three phase ac dc converter we have been discussing this closed loop control from past two lecture and this is the next part of that where we will go and see how we can get the closed loop control of this converter Now if we see the control objective there are primary two control objective is obviously regulating the output voltage at a desired value and the second is another one which is very important that while Regulating the voltage at the output, we also want that the current drawn from the AC source should be having the unity power factor. That means the phase angle between the phase current and the phase voltages is equal to 0.

In order to have the three-phase balance operation the voltage of the the phase voltages and the phase currents are actually dependent on each other that means we we can write $i_{sa} + i_{sb} + i_{sc} = 0$ and since we are controlling the current in order to achieve the unity power factor. So, if we are controlling the isa current if we are changing a phase current the b and c phase current will get impacted and if we change the b phase current a and c will change and if we change the c phase current then a and b will change so all the three quantities are dependent on each other. Now to make it independent we moved from three phase system to two-phase system now in two-phase system we have defined α and β axis which is nothing but the stationary reference frame where we see that since the alpha and beta are 90°from each other thus the quantity represented in α and β frame are mutually independent of each other since the α and β axis are 90°from each other thus whatever changes you do in the alpha component is not going to have any impact on the β component and any change in the β component will have zero impact on the α component and that's when you can independently control the α component and β component that's when you will get the independent control of the two phase quantities So, we move from three phase quantities to two phase quantity in order to make them independent and then from two phase quantity we move to dq frame which is synchronous rotating frame and where we ensure that the d axis or the direct axis is aligned along the supply voltage space vector.

The reason being because the supply voltages are the one which has the minimal deviation and we do not have any control on that so that's why that is the one of the reference space vector and we align our direct axis along the supply voltage space vector which is nothing but $\vec{V}_s$ and the quadrature axis is $90°$apart from d axis so thus the quantities expressed in terms of d and q axis are independent of each other that means d component of the space vector is mutually independent of the q component of the space vector and the d is perfectly aligned across the supply voltage space vector by ensuring that the V_{sq}component is equal to zero that's when the d axis is aligned is aligned along the $\vec{V}_s$. So, since we are just making Vsq component equal to 0, so whatever the $\vec{V}_s$ is there is nothing but has only the V_{sd} component and that V_{sd} component is actually determining the overall you know magnitude of source $\vec{V}_s$.

And since we have aligned our d-axis along the voltage space vector and this voltage space vector is rotating with the speed which is equal to omega which is nothing but the speed with which the voltage is varying with respect to time t. So, the omega corresponds to the line frequency which is nothing but $2\pi f_s$ which is nothing but the line frequency we have considered in our system and since this d-axis is aligned along this voltage space that means d and q-axis is also rotating with the same speed omega that's why it is also called as the synchronous rotating reference frame or sometimes also called a rotating reference frame now we can model our three-phase converter which looks something like this it has L it has R_s and these three phase switches. So, if we can model this converter using the dq axis frame then we can ensure that the quantities we obtain from the dq axis models that means the current I_{sd} current or an I_{sq} current which are the projections of current space vector on the d axis and q axis they are mutually independent of each other as they are $90°$ apart from each other and whenever we are doing any changes on I_{sq} there is no change on isd and whenever you are doing changes on I_{sd} there is no change in I_{sq} and so when we when we have derived this d axis model and q axis model we get this expression which is

$$V_{sd} + L\omega I_{sq} - v_{conv,d} = L\frac{d}{dt}I_{sd} + R_s I_{sd}$$

$$- v_{conv,q} - L\omega I_{sd} = L\frac{d}{dt}I_{sq} + R_s I_{sd}$$

Again, this is a cross coupling term. What we achieve from our conversion going from the you know three phase circuit to the alpha beta axis and then going to the rotating reference frame system modeling the system in the rotating reference frame. and when we see this one there are two prime objective obviously maintaining the output voltage and the second one is we have to ensure that our current in all the three phases are having the unity power factor that means what if the current is having a unity power factor it indicates my is space vector whatever is there which contains the combined information of you know all the three phases that means i_{sa}, i_{sb}, i_{sc} because from i_{sa}, i_{sb}, i_{sc} . We obtain α, β, $I_{s\alpha}$ and $I_{s\beta}$ component and from $I_{s\beta}$ and $I_{s\alpha}$ component we are getting the I_{sd} and I_{sq} component and then when we take you know this I_{sd} and I_{sq} component will actually corresponds to the I_s. So if we can ensure that this space vector is aligned along the $\vec{V}_s$ then we can ensure that in all the three phases the phase currents and the phase voltages the supply phase voltages are having zero phase angles that means having the unity power factor operation. So that means to have to have unity power factor operation if I can somehow ensure that $\vec{Is}$ aligned along the $\vec{V}_s$ then I can ensure that we have the unity power factor operation.

Now, this how we can ensure this alignment is done by making sure this $\Phi = 0$, that means what if I am making $\Phi = 0$ that means this $\vec{Is}$ is aligned along the $\vec{V}_s$ and this is space vector and voltage space vector is aligned along the d axis that means the $\vec{Is}$ only has the I_{sd} component and there is no I_{sq} component which indicate my $I_{sq} = 0$ and if my $I_{sq} = 0$ so I can write my $\vec{Is} = I_{sd}$ +j0, and accordingly we will get the $\vec{Is}$ and then we can just control our I_{sd}component and in that way we can ensure that the $\vec{Is}$ is complete perfectly aligned along the $\vec{V}_s$ and we can control the magnitude of this $\vec{Is}$ by controlling the I_{sd}value and whenever we are controlling the I_{sd}component we are not having any impact on the q component because q component we are making it equal to zero and that's when i can ensure that you know we have the independent control and i'm just controlling the in phase or d component of supply current and we are forcing it to be aligned along $\vec{V}_s$ and that's when we can ensure that we have in all the three phases the unity power factor and we can change the magnitude of current drawn by changing the I_{sd} component.

So, this is how we can get the independent control of the I_{sd} and I_{sq}component and now let's say if you wanted to inject some reactive component of current then we can make the I_{sq} component to be non-zero and then separately control the I_{sq} component and I_{sd}component and that's when you can also supply the reactive component of current and you can have the required active composition but however in our case since we are drawing current from the grid we wanted it to be having the unity power factor and that's when we are ensuring my I_{sq} component to be zero. That's when my $\vec{Is}$ is aligned along the $\vec{Vs}$ because this angle $\emptyset = 0$. Now if you look very carefully αβcomponent that means when you are converting i_{sa}, i_{sb}, i_{sc} to $i_{s\alpha}$, and $i_{s\beta}$ This α and β axis are stationary axis while this $\vec{Vs}$ or you can say the space vector which contains the information of all the phase ‘a’, phase ‘b’, phase ‘c’ voltages are actually rotating in ‘a’ space. Since it is rotating in a space, so if we look very carefully the alpha component and beta component is actually having or varying sinusoidally varying sinusoidally with a phase difference of 90^0 because see these are stationary and if we change our Vs component. So let's say if they are lying along the alpha so that's when your alpha component Is, pk and $\beta = 0$ and when it goes to β component α=0 and so that means it starts from here α component it starts from here Vs or you can say $\vec{Is}$, if it is here it starts from peak it goes to beta that's when it goes to zero and then it comes back 180^0 where it is maximum negative peak and then it again goes to this one where it is at zero and then finally it comes back here which Is, pk . So, we see that we have the sinusoidal variation like this going like this. So, our $i_{s\alpha}$ is β and our $V_{s\beta}$ and our v_{conv}, α , $v_{conv,\beta}$ voltages are actually varying sinusoidally with a phase shift of 90^0.

And why beta is 90^0? Because that is happening just 90^0 apart from, I mean the variation is 90^0 apart from this thing. And now this varies sinusoidally with a phase shift of angle theta with respect to time t. Why? With respect to time. here we are talking about space and here we have converted the information from this space to the time domain why we are saying time domain because we assume that this space vector is rotating with $\omega = 2\pi f_s$ corresponds to the line frequency that means a, b, c quantity is also varying with the same frequency f_s with respect to time.

So, we can correlate that space with respect to the time. So, that's when our $i_{s\alpha}$, and $i_{s\beta}$, quantity if you look you know the $i_{s\alpha}$, $i_{s\beta}$, $V_{s\alpha}$, $V_{s\beta}$, $v_{conv,\alpha}$, $v_{conv,\beta}$ this sinusoidally vary with respect to time.

And then from here if we convert it into I_{sd}, I_{sq} and V_{sd}, V_{sq}, $v_{conv,d}$, $v_{conv,q}$. Now if we look this particular quantities since this dq this space vectors which is $\vec{V}_s$ $\vec{I}_s$ and $\vec{v}_{conv,}$ space vector are rotating with this angular speed 'ω' having the fixed phase angle between them but they are all rotating with a speed 'ω' and since my dq axis is also rotating with angular speed 'ω' then if you look from the dq axis frame all the three space vector which is $\vec{V}_s$, $\vec{I}_s$ and $\vec{v}_{conv,}$ are looking like a stationary or stationary with respect to d and q frame because d and q frame is also rotating with omega speed and my all the three space weather is also rotating with 'ω' speed So, with respect to the d and q axis this all three quantities when they are represented in the form of d and q then we see that this d and q quantities are stationary quantities that means we can say they are the DC quantities.

So, what we have done from three phase bearing dependent quantity we converted into two phase independent quantities which are also varying sinusoidal with respect to time and then from that to mutually independent phase quantity we have converted into dq quantities which are a dc quantities. Now, since they have a dc quantities we can easily implement the closed loop control and use the controllers like conventional PI controllers you know conventional proportional integral controller. Since the dq quantities are DC quantities, we can apply conventional PI controllers to control dq , dc quantities what I mean by that here since we are controlling the supply current or the current drawn from the source. So that means we are controlling the I_{sd} and $I_{sq}$and we can do the controlling of I_{sd} and $I_{sq}$by using the conventional pi because if we take the conventional pi we have the pole which gets introduced at s=0 zero that means if we look a transfer function of k_p k_i.

$$k_p + \frac{k_i}{s} = \frac{k_p s+k_i}{s}$$

and that indicates it has the pole at s equal to zero pole at s equal to 0 that means you can apply very infinite gain at the dc that means at s = 0 and that's you can ensure that the feedback is actually following the reference and thus you can able to obtain a very effective closed loop control and since d and q quantities are independent of each other we can get mutually independent two phase or two loop structure to actually do the independent control on the isd and isq and that's when we can ensure that by properly defining that isq reference and isd reference we can ensure that we can able to regulate the output voltage as well as having the duty power factor operation now let us try to derive the closed loop control loop how the closed loop control loop look like so if you see our converter what we have is L and Rs and we have the three phase half bridge converter and this three phase half bridge converter is actually modulated using the pulse width modulation.

Assume we are doing the modulation using the sinusoidal pulse width modulation where we are ensuring the modulating wave which is Vm is actually varying sinusoidally and thus we can ensure that the average pole voltage variation at the output of these half bridges are actually having the sinusoidal variation. So, that is the dq axis model and if we see this L and Rs. So we have already taken the impact applying the voltages across these L and Rs so we have in these two equations we have actually kind of trying to capture the the dynamics which could have occurred by L and RS. I mean obviously we have represented in a time domain so that we could able to you know accommodate some of the dynamics which could occur because of L and Rs. However there is this converter also and assume the three half bridges modulated using sinusoidal pulse width modulation so what we are doing is we are having the carrier high frequency carrier like this very high frequency carrier and we have the modulating wave which is kind of looks very stationary with respect to the carrier wave because we have assumed that our fc carrier or similar to that of fsw is very very much greater than fs which is the line frequency.

So now let us see in this case what could have happened now assume you have done the closed loop control if you wanted to change this i_{sa}, i_{sb}, i_{sc} , you can only change because this side V_{an} and$V_{bn}$and V_{cn} are constant. so you can only change this the voltages which is appearing at the output of the half bridges in an average sense in a one cycle period now how you can change the output from these half bridges we are actually doing the averaging over the cycle period or you can say that over the switching period that means over the carrier cycle period so now when we are doing the averaging of that then we can change that average variation by changing this let's say if this was here changing this you know modulating wave to change the average pole voltage variation Since we are actually controlling the current from the source because this we cannot change. L and Rs value we cannot change once it has been designed. So only one way by which we can change.

If we can vary the output of the half bridges by changing the modulating wave. So this is our modulating wave. We are changing our Our modulating wave or modulating signal. Because carrier we are not going to change.

Because we are assuming we have the constant frequency operation. So now if we are doing this change. Now assuming this time to this time is nothing but Tc. which is also you can say that $T_s = \frac{1}{f_{sw}} = \frac{1}{f_c}$.

So now if this is the case so what has happened you know the best possible scenario is if I can change if I do this change at right at this point That means whenever the change occurs, it can occur directly at this point and then that particular change is captured at this instance.

That means at t, let us say at t equal to 0 instance. And the worst case scenario is, that means worst case scenario means let us say if this happens right after this point and I mean the time after which this change can reflect is after t equal to tc. So, the best case scenario is t equal to 0 and the worst case scenario that means there is a delay of one cycle time because that could have happened just right after this comparison has occurred. So, the best-case scenario is t = 0. The worst case delay what we can expect when we are doing this change in the modulating wave, the worst case delay in the response we can expect is one carrier cycle period.

So, we can say that average time delay in response towards change in modulating wave. Let us define tingi is nothing T_{sw} where T_{sw} is nothing but same as a carrier period switching period is same as carrier period which is nothing but equal to $\frac{1}{f_{sw}} = \frac{1}{f_c}$.

So that implies my average delay in response towards the change in the modulating wave is nothing but $\frac{T_{sw}}{2}$. Now this the average delay in response will be appearing at the output of this half bridges and if we assume this to have the you know the best possible case scenario is to have the a single order delay function so we can define the the transfer function of three phase half bridge we are only consider the habit we are not considering any delay which could have occurred due to the change in the current in inductor or change in the voltage across the capacitor so the transfer function of this three-phase half bridge we can just say that it is

$$T.F = \frac{G}{1+sT_d}$$

$$T_d = \frac{T_{sw}}{2}$$

and G is nothing but the gain G is nothing but we can write it is

$$G = \frac{\frac{V_0}{2}}{V_C}$$

that means when we are doing when we are having this carrier here we are going from 0 to 2Vc from 0 to 2Vc or - Vc to + Vc then when we are going from 0 to 2Vc we are actually applying either if we are making sure the modulating wave is here we are actually applying the zero voltage and if our modulating wave reaches to this peak value or to at 2Vc we are actually applying the V_0 voltage at the output of half bridge because when this modulating wave reach till this point let's say the modulating wave is here then at every instant of time my modulating wave is greater than the carrier wave and if my modulating wave is greater than the carrier wave I will always turn on the top switch and when I always turn on the top switch it is the voltage V_0 obviously with respect to this point we are applying at the pole of the hub bridge and then whenever the modulating wave is here at the least bottom then at that point always my carrier is greater than modulating wave that's when we will turn on all the bottom switches and when we will turn on the bottom switches then we will apply actually the zero voltage at the pole of this converter that means van if we take this as capital N then the voltage of $V_{aN} = 0$, so the gain what i get is nothing but V_0 whenever I am making sure my modulating wave is nothing but equal to 2Vc and that's when we can define this transfer function to be $T.F = \frac{G}{1+sT_d}$

and whenever there is a change in the modulating wave there will be change in the current because this side voltage is constant this side voltage is varying so there will be change in the current.

And thus the change in 3 phase currents will also reflect changes in I_{sd} and I_{sq} currents whose dynamics can be obtained by d and q axis models. Now let us define the d and q axis model in the form of frequency domain and then we can obtain the closed loop control block diagram. Now if you look very carefully over dq axis model what we have is we have represented in terms of time domain. we can take it to the frequency domain okay let us take in this way take it to the frequency domain, we can write SL we can take the Laplace on either side become($sL + R_s$) is nothing but if we can do ISD of S is nothing but what we are doing is minus V converter of D we are applying minus V converter of D And this particular term is actually coming along with this application of V converter.

$$I_{sd}(s) = \frac{-v_{conv,d}(s)}{(sL+R_s)} = \frac{-v_{conv}(s)}{(sL+R_s)}$$

So, in the closed-loop operation, we will ensure that these two things will get canceled out, and that cancellation we can do by adding the V_{ff}. So, we can add some V_{ff}. We can apply for the d-axis.

$$\left(sL + R_s\right)I_{sd}(s) = -\,v_{conv,d}(s) + V_{ff,d} + \frac{\omega L I_{sq}}{G} + \frac{V_{sd}}{G}$$

And similarly, we can do for the q-axis. We have sl plus rs isq of s, nothing minus v converter q,

$$\left(sL + R_s\right)I_{sq}(s) = -\, v_{conv,q}(s) + V_{ff,q} - \frac{\omega L I_{sd}}{G}$$

and we can then also add some $V_{forward}$ across the q-axis. We can write this $V_{forward}$ of the d-axis as nothing but We will add such feedforward such that we can actually cancel out these two terms. If we can cancel out these two terms, then we can ensure that there is no cross-coupling as well as this is the constant quantity.

So we can also eliminate that quantity as well. So that V_f could be

$$V_f = -\, \omega L I_{sq} - V_{sd}$$

And since we are having the gain G, we will represent this by gain G. We will thus divide it by gain G, so this when we multiply it with the transfer function of the half-bridge converter, which is $\frac{G}{1+sT_d}$,

then the G and G will get canceled out, and that voltage will be applied across the L and Rs in the circuit. Similarly, we can write for V_{ff}(q). Now, this V_f(q), if we see this, we will add such feedforward in the $v_{conv,q}$, such that this particular term will get canceled out, and that we can write this as nothing but $-\, \omega L I_{sd}$. If we can add these two feedforwards, we can ensure that this particular term gets canceled out, and that's when we can ensure there is no cross-coupling happening between the d-axis model and q-axis model. We can make both the axes, you know, I_{sd} and I_{sq}, to be independent of each other. So, after this feedforward term, we will add this ω because these are already there in the system. I_{sq} is obviously applied through the converter with a gain G, so we will divide by gain G plus V_{sd} by G. In the $V_{ff,q}$, we have $-\, \omega L I_{sd}$.

$$V_{ff,d} = \frac{-\omega L I_{sq} - V_{sd}}{G}$$

$$V_{ff,q} = \frac{\omega L I_{sd}}{G}$$

So, when this feedforward term gets added up here, we have also divided by G, and here also we have divided by G. So, when we add this feedforward term in this one, this feedforward term will actually cancel out the effect of this cross-coupling term I_{sq} term in the I_{sd} model and

I_{sd} term in the I_{sq} model. It will also cancel out this $\frac{V_{sd}}{G}$ effect as well, and that's when we can actually cancel out the effect of these terms.

So, let us draw the closed-loop control diagram of the converter. Our primary objective is obviously we are actually $V_{o,ref}$. Whatever $V_{o,ref}$,you are having, then this $V_{o,ref}$, you are actually comparing with $V_{o,f}$ or $V_{o,actual}$. Let us define feedback, obviously it is in the 's' domain. Domain, and this we will send it to the voltage controller. This voltage controller will actually, after passing through this limit term, since we know that we are doing the unity power factor operation, that means we are actually aligning our IS space vector along the $\vec{V}_s$. That means we are ensuring our q-component of current is zero and only we have the I_{sd} component of current, so whatever there is change in the output voltage that output voltage need to be compensated that means extra current to be drawn from the source or less current to be drawn from the source that both the things has to be done using the I_{sd} component so here we have $I_{sd,ref}$, this will actually determine by $I_{sd,ref}$ this I will compare it with $I_{sd,f}$ obviously in the 's' domain we are doing and this we are comparing with $I_{sd,ref}$ and this will then go through current controller $I_{sd,}$ current controller.

Now since this is implemented in the converter so the output of this will be we can say that it is $v_{conv,d}$, we look $v_{conv,d}$, we are getting here and we have to multiply it with minus sign this we will multiply it with the (-) sign and then or just let us take the i mean here first the plus sign and this will be added up with the if you look very carefully we are now adding the feed forward term the first feed forward term is

$$feed\ forward\ term = \frac{\omega L I_{sq}}{G}$$

So we will add we will add this feedforward term, that term we will add and this we will just send it to negative sign because both are of negative sign and this will be nothing but my vsdyg and the output of this will be if you look very carefully we have already defined this and this feed forward term that means already this will get cancel out so this is the feed forward term which we are applying this is already there in the model so we can say that if we look this one carefully this is already there in this model and because of adding this feed forward this to get cancel out this all will get cancel out so we will leave that apart because of adding this feed forward term and this will be actually finally going to the $converter\ T.F = \frac{G}{1+sT_d}$, this is converter transfer function or three phase half bridge transfer function and this is actually coming back here and then you are applying it to this particular thing you are applying it across $sL + R_s$, $\frac{1}{sL+R_s}$

so here we were applying actually my $v_{conv,d}$ from this $v_{conv,d}$ and here it was in the modulating wave here we get it in the actual sense and that will be actually defining my I_{sd} component.

So, we will send it through current sensor and we will define this current sensor to have this transfer function K1 divided by 1 plus ST1 and this IHD will come from there.

$$I_{sd,ff}(s) = \frac{K_1}{1+sT_1}$$

And then we will just do the multiplication factor K. We will define what is K as we go along. This will actually determine my I_{sd}.

I converter if you look that is i_{conv}, it is here so from the I_{sd} we have to define the i_{conv} and after this i_{conv} we can pass it through $\frac{1}{sC}$ to actually give me my output voltage V_O and that V_O, we will actually take feedback using the voltage sensor with a gain $I_{sq,ff}(s) = \frac{K_2}{1+sT_2}$

and this will be actually written feedback like this similarly this is for the of the d component of the circuit now we also have the q component of the circuit and since we want to have the unity power factor.

So, we can define another independent volt loop which is nothing but a $I_{sq,ref}$ we will define and this $I_{sq,ref} = 0$ and this we will compare it with the feedback $I_{sq,ff}$ obviously in terms of 's' this is nothing but going to current controller and then after that we have to this we will define $v_{conv,q}$ this will be , now if you look very carefully minus and this will be $+ V_{sq}$, we have to do so that will be plus we say $+ V_{sq}$ which is $\frac{\omega L I_{sd}}{G}$.

And this is then going to $\frac{G}{1+sT_d}$, and this is then going to $\frac{1}{sL+R_s}$, and that will give you my $I_{sq,ff} = \frac{K_2}{1+sT_2}$ value, and this will be feedback. Through the current sensor, whose transfer function is $I_{sd,ff}(s) = \frac{K_1}{1+sT_1}$, Now, this $\frac{K_1}{1+sT_1}$ is the transfer function of the current sensor, and $\frac{K_2}{1+sT_2}$ is the transfer function. Of voltage or output voltage sensor. And if you look where $I_{sq,}$ is, this $I_{sq,}$. we can take from this place itself, and this $I_{sd,}$ we can take from this place itself—the feedback itself. In that way, we can ensure the $I_{sd,ff,}$ is following the $I_{sd,ref,}$, and $I_{sq,ff,}$ is following the $I_{sq,ref,}$. And that's when we are ensuring that we are having the multi-power factor operation from the three-phase AC to DC converter.

So, we will discuss further understanding on how to design these controllers in the next class. And thank you very much for patiently listening to this lecture. Thank you.