CHARGING INFRASTRUCTURE

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Week-06

Lecture-29

Lec 29: Closed loop control of three-phase AC-DC converter-IV

Hello everyone welcomes to the lecture number 29 of this NPTEL lecture series on charging infrastructure and in this lecture, we will continue our discussion on the closed loop control of three phase AC to DC converter. So let us recap some of the things we have discussed we have started with our control objective which was to control the output voltage or regulate the output voltage at a desired value and along with that maintaining the unity power factor operation when we are drawing current from the grid. So to do that, we have for balanced three-phase operation, we understood that the current which is drawn from the grid as well as three-phase voltages are not independent of each other, they are dependent on each other. That means once we are changing one of the phase currents, other phase currents are also getting impacted because of the balanced three-phase operation. So, to do that what we did was we have defined the two-reference frame one is αβ reference frame which is a stationary reference frame where there is a voltage space vector which is rotating in a space with angular speed equal to $2\pi f_s$ and the α and β frame are stationary in the space.

And because of that since alpha and beta are 90^0 apart from each other, the component of $\vec{V}_S$ along the alpha axis and beta axis are independent of each other. That means whenever you are changing the α component, the β component is not getting impacted and whenever you are changing the β component, α component is not getting impacted. impacted and that's when we can achieve the independent control of the two αβ component that is the stationary reference beam. Similarly on the similar line so we then define another reference frame which is called as the dq reference frame and that is also called as a synchronous rotating reference when a rotating reference frame. Because we align our d-axis in such a manner that the d-axis is aligned along the rotating voltage space vector. That's when by making sure the component of $\vec{V}_S$ along the q-axis is equal to 0.

That's when we can ensure that d-axis is completely aligned along the voltage space vector. And we then define the current space vector and if we ensure that Is component is equals to 0, that is when we ensure that the $\vec{I}_S$ is perfectly aligned along the D-axis and as the D-axis is aligned along the voltage $\vec{V}_S$, that is when we can ensure that my $\vec{I}_S$ and $\vec{V}_S$, are completely aligned and that is when we can say that in all the three phases we have the unitary power factor operation. then we define our dq axis model where we saw there are some cross coupling terms and some constant term that we understood we have removed those terms by putting the feed forward terms and that's when we have made the two independent loops this is my q axis or you can say the q axis loop and this is the d axis loop and since we know that we are actually aligning our $\vec{I}_S$ along the $\vec{V}_S$, that is we are doing it by making sure my I_{sq} reference is equal to 0 and that's when we can ensure we have the unity power factor operation of this three-phase AC-DC converter. since we know that our prime objective is to regulate the output voltage depending upon whatever the reference we have selected and that if there is a mismatch in that that will give the difference to the I_{sd} component because my I_{sq} component is 0 so it is only determining the I_{sd}component and because if the I_{sd} component increase that means the amount of current or the magnitude of current drawn from the source will either increase or decrease accordingly depending upon what is the output voltage of this converter we are having.

Then after that, we get the converter voltage, which will be applied by the three-phase inverter. Then we have two feed-forward terms, and finally, we have defined the transfer function converter transfer function, which applies the voltage across the series connection of L and Rs, where Rs is nothing but the equivalent series resistance of the inductance. That will give my I_{sd}. From that I_{sd}, we have evaluated the Vo, and that we will feed for feedback via the voltage sensors whose transfer function because, you know, the voltage sensor also has its own bandwidth and its own gain. This is needed because this voltage could be 400 volts, but this voltage you are setting up in the microcontroller, and that voltage could be either 3.3, 1.8, or 2 V, depending upon the microcontroller you are using or the voltage level of the microcontroller. So that much gain you have to provide from the voltage sensor. So this is nothing but your transfer function of the output voltage sensor. Nothing but this K2 is the gain, and the denominator indicates the bandwidth of the sensor, corresponding to 1/T2. For simplicity, we assume that the sensor has a first-order response, so that's why we have taken a single-order transfer function. Similarly, similarly for the I_{sd}, we are actually feeding it back into the loop. So that we are sending it through the current sensor. Again, the current sensor we are just taking, you know, the gain to convert the actual current into the value of that current which is been put inside the microcontroller. And this is nothing but the transfer function of the current sensor, and this is assuming that this current sensor has some bandwidth, that means beyond a certain point, there will not be any gain you will obtain from the sensor. And that we approximated with the single-order transfer function, so we can get 1/ST1 as the pole, which will be representative of the dynamics of the current sensor. Similarly, in the q-axis loop, we have only the current loop; we do not have the voltage loop because we want, ideally, our Is reference to be 0. Then only we can ensure our $\vec{I}_S$ is aligned along the d-axis, which is aligned along the supply voltage space vector. And that is when we can ensure that we are actually drawing unity power factor current from the source. Now, let us start understanding how we can find out this particular controller. How we can find out these controller parameters. So, let us try to find out how we can obtain this controller, how the controller looks like, and how we can calculate this K value, this current controller, current controller, and voltage controller, and what are the guidelines to do that. Let us calculate that, and then we will see overall how we can define our closed-loop control.

And let us derive our closed-loop control. Now, let us first just take the current loop where we have $I_{sd,ref}$ coming in. And we have $I_{sd,ff}$ coming in. And we have a current controller. So here we have just taken the current loop.

Just the, if we look into only this loop. And this loop and this loop is nearly same. Because the feed forward term will not introduce any dynamics. They are just constant values either increasing or decreasing the $V_{conv,d}$ and $V_{conv,q}$ values. So we can neglect them and then we will have just this loop itself.

So let us define the current controller which is just a PI controller which is nothing but

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

which is nothing but a standard PI controller we will define this is for current controller so k_{pc} and k_{ic} for the current loop and that's when we will get after this this particular thing will be going to just the converter transfer function which is nothing but G by just the half bridges transfer function is as:

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

and that is actually going to $\frac{1}{sL+R_s}$ and that is nothing but my $I_{sd,}$ which I am getting and which will be feedback through the current sensor is follows:

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

Now in this particular case let us define the closed loop transfer function of this, so let us define closed loop transfer function. So, my closed loop transfer function will be my $I_{sd,}$ which is going I mean at the output divided by my reference which I am setting up is nothing but let us say the current controller. Let us simplify the current controller. So current controller is nothing but $\frac{k_{pC}+k_{iC}}{s}$ is nothing but we can write k_{pC} we can take it out, this we can just do it So this is your current controller. So this current controller is

$$\frac{k_{pC}+k_{iC}}{s} = \frac{k_{pC}\left(s+\frac{k_{iC}}{k_{pC}}\right)}{s}$$

$$\frac{1}{sL+R_s} = \frac{\frac{1}{L}}{s+\frac{R_s}{C}} = \frac{\frac{1}{L}}{s+\frac{1}{T_s}}$$

$$\text{Where, } T_s = \frac{R_s}{L}$$

So, in this particular current loop, one simple approach to obtain the current controller parameters is by cancelling out the pole associated with L and R_s with the 0 in the current controller which will give us the condition to arrive at the current controller parameters. Thus, we can write

$$\frac{k_{pc}}{k_{ic}} = T_s$$

(A)

So, this is the, this is one condition we are arrived at.

I am canceling out this pole with this 0. Now, we can further simplify this loop and write from the closed-loop transfer function in this loop, which can be written as

$$\frac{I_{sd}(s)}{I_{sd,ref}(s)} = \frac{\left(\frac{Gk_{pC}}{L(1+sT_d)s}\right)}{1+\frac{Gk_{pC}K_1}{L(1+sT_d)(1+sT_1)}}$$

$$\frac{I_{sd}(s)}{I_{sd,ref}(s)} = \frac{Gk_{pC}(1+sT_1)}{s(1+sT_d)(1+sT_1)L+Gk_{pC}K_1} \qquad (1)$$

and let us define this as equation number 1. In equation number 1, what we have is $\left(1 + sT_d\right)\left(1 + sT_1\right)$, so this I can write as

$$\left(1 + sT_d\right)\left(1 + sT_1\right)=1 + s^2T_dT_1 + s\left(T_1 + T_d\right)$$

Now, if you look very carefully,

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

which is T_{sw} being nothing but the switching period or the carrier period, and my T1, corresponds to the bandwidth of the current sensor. And if you look very carefully, both T_d and T_1 are very small quantities. For example, let us take a switching frequency of 10 kilohertz; then, the T_{sw} is 100 microseconds, and the T_d value is 50 microseconds, while the T_1 generally will be taken at least 10 times smaller than the T_{sw} value. Or switching cycle period, so it will be around 10 microseconds. So if we do the product of T_d and T_1, it will be very small, nearly 0.5 nanoseconds. So we can write that T_1 are small quantities, small values, so that's when we can say the product of T_d times T_1 is very small and it is. nearly approximated to 0, we can say. So that means we can write

$$\left(1 + sT_d\right)\left(1 + sT_1\right) = 1 + s\left(T_1 + T_d\right)$$

I mean, this is the approximated value. And then from here, what we can do is we can mention $T_1 + T_d$ is,

$$T_1 + T_d = T_\sigma$$

And that's when we can write it as

$$\left(1 + sT_d\right)\left(1 + sT_1\right) = 1 + sT_\sigma$$

From eq.(1),

$$\frac{I_{sd}(s)}{I_{sd,ref}(s)} = \frac{Gk_{pC}\left(1+sT_1\right)}{s(1+sT_\sigma)L+Gk_{pC}K_1}$$

so, when we rearrange this one. we will get the value as

$$\frac{I_{sd}(s)}{I_{sd,ref}(s)} = \frac{Gk_{pC}\left(1+sT_1\right)}{T_\sigma L\left(s^2+\frac{s}{T_\sigma}+\frac{Gk_{pC}K_1}{T_\sigma L}\right)} \quad (2)$$

and this we will define as equation number 2 this particular equation we can compare with compare with standard second order transfer function second order closed loop transfer function transfer function which is

nothing but you can let's say $2\xi\omega_n$ because you know if you look the denominator of the tender second order transfer function is nothing but $s^2 + 2\xi\omega_n + \omega_n^2$, that's denominator. We can say second order second order closed loop transfer function, closed loop transfer function we can say. Now, if we compare this and this denominator of equation number 2, what we are going to get is, we will get

$$2\xi\omega_n = \frac{1}{T_\sigma};\ \omega_n^{\ 2} = \frac{Gk_{pC}K_1}{T_\sigma L}$$

Now this particular thing if we keep $\xi = 0.707$, so we will get

$$2\frac{1}{\sqrt{2}}\omega_n = \frac{1}{T_\sigma}$$

So if we take the square on both side what we will get is

$$\omega_n^{\ 2} = \frac{Gk_{pC}K_1}{T_\sigma L}$$

$$\omega_n^{\ 2} = \frac{1}{2T_\sigma^{\ 2}};$$

Further from previous slide what we can write down is that $\omega_n^{\ 2} = \frac{Gk_{pC}K_1}{T_\sigma L}$

and that when we simplify what we will get is k_{pC} is

$$k_{pC} = \frac{1}{2GKT_{\sigma_1}} \qquad \text{(B)}$$

and this is nothing but the current controller parameter the proportional parameter what we will get and this if you see from this to this first condition let us define this as condition number A and let us define this equation as equation B from A and B we can calculate the current controller parameters, that is how you can design your current controller.

And since we can design our current controllers, we can able to do the inner I_{sd} current loop control and the I_{sq} current loop control. Now, after this, let us do the voltage control loop. To do this, from equation 2, we can just write

$$\frac{I_{sd}(s)}{I_{sd,ref}(s)} = \frac{\left(1+sT_1\right)}{K_1\left(2\xi^2 s^2+2T_\sigma s+1\right)} \qquad \text{(putting (B) in eq. (2))}$$

This is again, we got it by putting b in equation 2. We will get this, so in this one we have a zero, and this zero is at a very high frequency. In this denominator, we have an s-square term. Now, if we look very carefully, if we look at our overall trans loop, In this loop, we know that our outer voltage loop is slower compared to the inner current loop because then only whatever changes occur or ensure at $I_{sd,ref}(s)$, that $I_{sd,ref}(s)$ will be tracking that particular change. Thus, we must ensure that our outer voltage loop is much slower compared to the inner current loop. Generally, the outer voltage loop is actually tracking only the DC quantity because the output is a DC quantity. So, our outer voltage loop is very slow. Since our outer voltage loop is a slower loop, thus the dynamics

Due to the zero at $s\frac{1}{T_1}$ equal to 1 by t1 frequency, that means due to the zero and due to the s-square terms in the denominator can be neglected. Why? Because let's say if we take This voltage loop is a slower loop, so the frequency corresponding to that slower loop is very small, near to s equal to zero. So, when we have frequency corresponding to dynamics closer to zero, that means s is close to zero value, and the zero in the numerator, which is kept at $\frac{1}{T_1}$, will have very negligible contribution towards the dynamics. For smaller frequency, the product of $\left(1 + sT_1\right)$is very small. Since both $\left(1 + sT_1\right)$values are very small quantities. Similarly, in the denominator, the S-square term can be neglected as S corresponds to a smaller value.

And thus, the S-square term will be an even smaller value. So, we can say that this particular part and this particular part can be neglected. Neglected due to the slower outer voltage loop. So, finally, our $I_{sd}(s)$ and $I_{sd,ref}(s)$, obviously, these are closed-loop transfer functions. This one is

$$\frac{I_{sd}(s)}{I_{sd,ref}(s)}\Big|_{CLTF} = \frac{1}{K_1(2sT_{\sigma_1}+1)} \tag{3}$$

let us define this as equation number 3. This is nothing but the closed-loop transfer function if I write the closed-loop transfer function of the inner current loop. Now, let us see how the voltage controller parameters will be dependent.

So let us try to write down the voltage loop. In the voltage loop, if we see, we have the $V_{o,ref}$, we have$V_{o,ff}$. This is going to the voltage controller, which we define on the similar line as that of the current $\frac{k_{pv}+k_{iv}}{s}$, similar line as that of the current controller. This will be going to $I_{sd,ref}(s)$ and this is $I_{sd,ref}(s)$. This is the overall transfer function, which goes to $\frac{1}{K_1T_\sigma s+1)}$, and this finally gives me I_{sd}. Then this particular I_{sd} is going to a block again called K, and that will be going to i_{conv}. That i_{conv}will be going through the capacitor having the impedance $\frac{1}{SC}$, which will give me my dynamics of the voltage controller. Then I have the outer voltage sensor; the transfer function corresponds to that, that will be taken feedback.

Now in this one, in order to assign what could be the best possible k_{pv} and k_{iv} values. So what we can do is we can just define an open loop transfer function. Which will just say OLTF. And open loop transfer function.

$$\left.\frac{V_0(s)}{V_{0,ref}(s)}\right|_{OLTF} = \frac{k_{pv}.K.k_2\left(s+\frac{k_{iv}}{k_{pv}}\right)}{s^2CK_1(1+2sT_\sigma)(1+sT_2)} \quad (4)$$

So, we can say just $V_0(s)$ divided by $V_{0,ref}(s)$. This OVLTF is nothing but we just do the multiplication of that.

Now again, in this particular thing, let us define this as equation number 4. Let us define this

$$\left(1 + 2sT_\sigma\right)\left(1 + sT_2\right) = 1 + 2s^2T_\sigma T_2 + s\left(T_2 + 2T_\sigma\right)$$

And if you look very carefully, this T_σ and T_2 are small quantities, a small quantity. That's when the product of T_σ and T_2 is nothing but equal to zero. Or nothing but nearly equal to 0, very small you can say so. Thus, we can say that

$$\left(1 + 2sT_\sigma\right)\left(1 + sT_2\right) = 1 + 2sT_\sigma T_2$$

$$2T_\sigma + T_2 = T_\delta$$

$$\left(1 + 2sT_\sigma\right)\left(1 + sT_2\right) = 1 + s\left(T_2 + 2T_\sigma\right) = 1 + T_\delta s$$

and that we can just write down this one value to be $1 + T_\delta s$. And thus, we can say we can finally write our equation number (4) to be

$$\left.\frac{V_0(s)}{V_{0,ref}(s)}\right|_{OLTF} = \frac{k_{pv}.K.k_2\left(s+\frac{k_{iv}}{k_{pv}}\right)}{s^2CK_1 1+T_\delta s}$$

Now, this is the open-loop transfer function we can define. So, in this, if you look very carefully, if you try to draw the Bode plot of this particular system, what just the gain plot if you try to draw. So, what we have is gain in dB.

If we do, and this is nothing but with respect to frequency, we see we have two poles at s equal to 0. That means we are having very high values and we are falling down. Since we have two poles, we are falling down with minus 40 dB per decade. And then what we have is we have one zero and we have one pole. Now, if let us say the pole is placed at a lower frequency as compared to the zero, then what will happen?

After this, it will fall down with minus 60 dB per decade. And then after zero, it will be falling by minus 40 dB per decade. And the other possibility could be, let us say we keep our zero at this point, which is $\frac{k_{iv}}{k_{pv}}$. This zero if we keep at this point, then after this we have minus 20 dB per decade the slope, and then after that slope what we will have is at 1 by T delta frequency we have gain which is again falling with minus 40 dB per decade. Now, at this point, let us say this 0 dB line, and we have the zero crossing at wc. Now, if we look very carefully, we know that if we have gain Bode plot, if it is crossing the 0 dB line with a slope of minus 20 dB per decade, then we can get a higher phase margin as compared to when it is falling with minus 40 dB per decade or minus 60 dB per decade. So, we can say that in this one if we. cross the 0 dB line with a slope of minus 20 dB per decade, then we can say that a high phase margin can be achieved. That means We will get stable closed-loop operation compared to if we have minus 40 dB per decade or minus 60 dB per decade. It's primarily because if we look very carefully, we just plot the phase plot of this with frequency. At this point, we actually start our thing from - -180^{o}. So our phase plot will be having, you know, this is kiv by kpv, and this is 1 by t delta. So we are having minus 180 degrees because we have an s square term. And then, when we have a zero, we have a good, you know, we have some addition of phase because of the 0 at this place. And then after that, we will again fall back to -180^{o}after, or we can say we have this one 0, and then somewhere at this point After this point, we will fall to -180^{o}, somewhere like this, not accurately drawn but somewhere like this. So this is the thing we can obtain. This is the phase margin we can obtain. That means how much away from minus 180 degrees we are when we plot the phase plot of the open-loop transfer function. This is the phase plot of the open-loop transfer function. This is phase, and this is what we get the phase margin.

So, if we ensure this minus 20 dB per decade fall, then we can ensure we have a good phase margin. That means we can make sure the phase plot is that much away from -180^{o}, and that is the same thing we will do over here by keeping our zero smaller than our pole. So, one possibility could be we can put our zero crossing at the geometrical mean of this zero and pole. This is one possibility so that we can find some relationship. So where we can get $\frac{k_{iv}}{k_{pv}.T_{\delta}}$, and this zero cross, let us define this as some factor times $1/T_\delta$. And if we try to find out, we will get a square t delta to be equal to kpv by kiv. Now, this is one. That means we can say kpv by kiv is nothing but a square u delta. Now, this is one of these things. Let us define this as c. So, from c, we can get this relationship.

$$aT_\delta^2 = \frac{k_{iv}}{k_{pv}}$$

$$\frac{k_{iv}}{k_{pv}} = aT_\delta^2 \qquad \text{(C)}$$

$$T_\delta^2 = C$$

Now, we know that at w equal to ωC, my open-loop transfer function

$$\frac{V_0(s)}{V_{0,ref}(s)}\Big|_{OLTF} = 1$$

So you can find out the gain over here, and then we can put this term in that particular gain. Finally, we will get

$$k_{pv} = C\frac{k_1}{k_2 K a T_\delta} \qquad \text{(D)}$$

Now this is value d, and from c and d, we can calculate our voltage controller parameter. From C and D, voltage controller parameters can be obtained. So this is how we can ensure we will get the voltage controller parameters and current controller parameters. Still, we don't know what our value of k is. So let us try to find what could be our value of k. To obtain k, what we can do now is a simple thing, which is the power balance. So we can write our three-phase power The three-phase power, since we have unity power factor operation, we get ,

$$3\text{-}phase\ power = \frac{3V_{s,pk} \cdot I_{s,pk}}{2} \qquad (1)$$

Why we are getting by 2? Because Vs peak by root 2 and Is peak by root 2 is the RMS values and V phase RMS, I phase RMS, 3 times of that, we will get 3 phase power. Similarly, we can write

$$2\text{-}phase\ power = V_{sd}I_{sd} + V_{sq}I_{sq}$$

and we know that our V_{sq} is equals to 0 and I_{sq} is equals to 0 and we know that V_{sd} is

$$V_{sd} = \frac{3V_{s,pk}}{2}; \quad I_{sd} = \frac{3I_{s,pk}}{2};$$

so we can say that our two-phase power is

$$2\text{-}phase\ power = \frac{9V_{s,pk} \cdot I_{s,pk}}{4} \qquad (2)$$

This is defined as 1 this is defined as 2 , from 1 and 2 we can say that we can say that the three phase power is

$$3\text{-}phase\ power = \frac{2}{3}(2\text{-}phase\ power) = I_{conv}V_o$$

$$3\text{-}phase\ power = \frac{2}{3}V_{sd}I_{sd} = I_{conv}V_o$$

$$I_{conv} = \frac{2V_{sd}}{3V_o}I_{sd}$$

So, from here we can say

$$k = \frac{2V_{sd}}{3V_o}$$

Similarly, we can say our k1 value which is the gain of the current sensor maximum voltage of of controller or you can see the if it is 1 it is 1 if it is 3.3 it is 3.3 it all depends upon that divided by 3 by 2 times maximum value of i mean supply current that means if is peak is let's say 20 ampere then it is 3 by 2 times of 20 ampere similarly k2 we can say is nothing but maximum voltage

of controller divided by output voltage let's say if here we have 400 volt and here we are giving one volt as a v i mean one volt corresponds to 400 volt then our k2 value will be nothing but 1 by 400 similarly for the case of current as well this is what we can obtain on the k1 and k2 value if you look very carefully in this particular system we still have one quantity which is we have missed one quantity which is a so this a value is the one which will actually determine your phase margin whatever the value of phase margin you will take accordingly your things will be determined. So let us here if you see in this one if we take a = 2 from this transfer function you can calculate your phase value and from there you can calculate this thing. So you will say that your phase margin will be somewhere nearly equal to 37^o or precisely it is 36.86^o. So this phase margin is sufficiently enough that means my phase at at w c is 37 degree away from -180^{o} because the moment it touches -180^{o} we will have one stability in the system so we can say that if we keep our a equal to our phase margin equal to 37^{o}. Now this how we get this phase margin if we find out phase angle at wc of this thing is

$$\varphi_{\omega C} = tan^{-1}\left(\omega C \frac{k_{pv}}{k_{iv}}\right) - tan^{-1}\left(\omega C T_{\delta}\right)$$

$$\varphi_{\omega C} = tan^{-1}\left(\frac{1}{aT_{\delta}} + T_{\delta}\right) - tan^{-1}\left(\frac{1}{aT_{\delta}} + T_{\delta}\right)$$

$$\varphi_{\omega C} = tan^{-1}(a) - tan^{-1}\left(\frac{1}{a}\right)$$

$$PM = 180 + \omega C$$

$$a = 2\, that\ gives$$

and if we keep our $a = 2$ that gives and if we keep an equal to 2, we will get actually value to be equal to phase margin to be equal to nearly equal to 36.86 degree.

So, this is how we can keep either $a = 2$ or $a = 4$and accordingly we will get the required phase margin. So from here we can easily calculate our voltage controller parameter, current controller parameters and that's when we can design our closed loop control.

So let us see how we will make our entire closed loop using this you know independent control method like going into dq model and doing APC. And we are making $\vec{I}_s$ aligning along the $\vec{V}_s$ and since we are controlling the the angle and as well as amplitude of the vector we can say that this is also called as the vector control approach vector control approach or you can say the vector control of three-phase ac to dc converter.

Now if we have these three phases our inverter this we have used MOSFET we can also use IGBT with freewheeling diode here we have used MOSFET so we have three half bridges we have see R_L L $R_S$we know how we can calculate this L C and how we can size our switches then. Since we have to we are actually sensing the output voltage V_o and we are sending it to our closed loop control so we will be sensing this through voltage sensor to voltage sensor we are sensing and that we are sending it through our voltage sensor transfer function to the feedback to the $V_{o,ref}$ and that we will compare and then we go through the voltage controller we already know how we can design the parameter of voltage controller after that the limit to ensure how much maximum current can be flowing in the circuit that limit will actually define my $I_{sd,ref}$ and then I will be taking the $I_{sd,ff}$

and then having the current controller again we know how we can calculate our current controller parameters I mean if we assume it to be a conventional PI controller then limit and then feed forward term nothing but V_{sd}/G then $-\ \omega L V_{sd,ff}/G$ and similarly in the $I_{sq,}$ loop $I_{sq,ref}$, we are making it equal to zero that's when we are ensuring that$\vec{I}_s$ is aligned along the supply voltage space vector and that's when we can say that we are achieving balanced three-phase operation with unity power factor current drawn from the source and then we will have the our current controller we know how we can design our current control parameters limit and then finally one one feed forward term to actually negate the cross coupling effect which is $\frac{\omega L I_{sd}}{G}$ that we know we have already derived in our dq axis model and then after this we will get our $v_{conv,d}$, $v_{conv,q}$ and that will be sending from dq to abc to get our three modulating wave which is you we can say that V_{ma}, $V_{mb}$and $V_{mc}$and that we will actually modulator is nothing but comparing this modulating wave with the triangular carrier going from 0 to $2v_c$ and that's when we will get the required S1 S2 S3 S4, so gate pulses because we will just do the comparison if my modulating wave is greater than carrier then top switch is on if in that phase and if the modulating wave is smaller than the carrier then my bottom switch is on in that in that phase and that gate signal will be going to do this getting of these switches now if you look very carefully we also have this feedback to be generated this feedback isd feedback is coming over here and $I_{sq,ff}$is coming over here while if you take isq isq feedback is coming in the field i mean cross coupling term to negate the cross coupling term and isd feedback is used to actually negate the cross coupling term in the q-axis model. So now if you look very carefully, so for that how we can generate this is$I_{sq}$and $I_{sd,ff}$ for that we will sense a b c phase current and that through the current sensor since we have three phases so since we have three phases. So we are actually sensing three phase currents three phase currents and that is actually going to the filter which is nothing but $\frac{k_1}{1+ST_1}$ and then from here we will convert abc to dq and we are while doing abc to dq we will go from abc will go to alpha beta and from alpha beta will go to dq and if you recall how we can do this a,b,c to the αβ and dq we need angle theta information over here now this angle θ information is need to be generated now this angle theta information can be generated just by sensing this van V_{aN} and V_{cN} voltages and then we convert this abc to dq abc to dq means first abc to αβ and then αβ to dq that conversion we are doing and while doing this dq we are using theta and it we are using the same θ to generate my V_{sd} and V_{sq} and now since I can ensure my d axis is aligned along the voltage space vector if i can ensure that V_{sq} component or the component of supply voltage space vector along the q axis is equal to zero that is what we are doing over here we are giving V_{sq} reference equal to zero through the controller it could be you know traditional pi controller classical π controller you can use

And then the output of this will be nothing but the w because you are aligning the d axis along the voltage space vector. So basically aligning means you are changing the angular speed with which those d and q-axis is rotating because we are making so d and q-axis goes and get locked with the voltage space vector. so that's why we are seeing and that we are doing by making $V_{sq} = 0$ so from there we are also taking our feed forward term because mostly our grid frequency or because the line frequency is nearly 50Hz then there will be slight variation in the in that frequency so it varies around that 50 Hz. So that's why that feed forward term we have provided now the con this controller has to work to ensure that whatever the δ disturbance which is happening in the frequency that has to be taken care and then after this one we will have this integration and this integration will actually give me my theta information because this will be my total my actual line frequency and that line frequency is actually this is you can say w controller output and this one is added with feed forward to get the w which is actually getting integrated to give you theta information

And this theta information you can limit it between 0 to 2π and once it crosses 2π you can again reset it to 0. So we can get the theta information. So, theta will be actually varying like if you see this one it goes from 0 to 2π then 0 to 2π 0 to 2 2π. 0 to 2 2π then again 0 to 2π and this time period is nothing but t= $\frac{1}{f_s}$ or line frequency we have. So, from here we get the theta and that theta we will use to generate V_{sd} and V_{sq}.

So, when we do that and then if we make sure $V_{sq} = 0$. So, we are slowly aligning our d-axis along the supply voltage space vector. And that's when we can ensure the theta we are getting is synchronized with the grid supply voltage. That θ, we use the same theta from here; we will use the same theta over here to convert the V_{conv}, d and q values to a,b,c values. That's when we ensure that the modulating wave accordingly gets synchronized with the grid, or we can say the supply voltage. That is how we can ensure that we have synchronized operation, meaning we have unity power factor operation from the grid. Now, this particular part is essential. This particular part, from you can say here to the generation of theta, is nothing but called the PLL (phase-locked loop). So, we are ensuring that the d and q axes get rotated and locked with the voltage space vector, which itself is rotating in space with an angular speed the same as the speed with which the voltage varies with respect to time. Or you can say it is rotating with an angular speed w corresponding to the line frequency.

So, this is how we can achieve unity power factor operation along with regulating the output voltage V_o at the desired value. That is how we can ensure the closed-loop operation of a three-phase AC-to-DC converter. Thank you very much for listening to this lecture. Patiently, we will continue our discussion ahead, covering the isolated DC-AC converter in the next lecture.