Power Quality Improvement Technique
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Lecture – 28
Grid Connected VSC with Inner Current Control

Welcome to our NPTEL courses on the Power Quality Improvement Technique. We are discussing about the Grid Connected Voltage Source Converter. We have discussed about the outer voltage control loop and 'dq' frame of reference. We are going to discuss the inner current control loop and also the phase lock loop. That is one of the important aspects in our voltage source converter in a grid connected operation.

So, let us talk about the current control. Since we have not connected any resistance. For the sake of operation, we have shown in a voltage mode because there is a lump resistance that has been represented there. We will neglect the resistance in our previous equations of equation 5. Please refer to our previous lectures.

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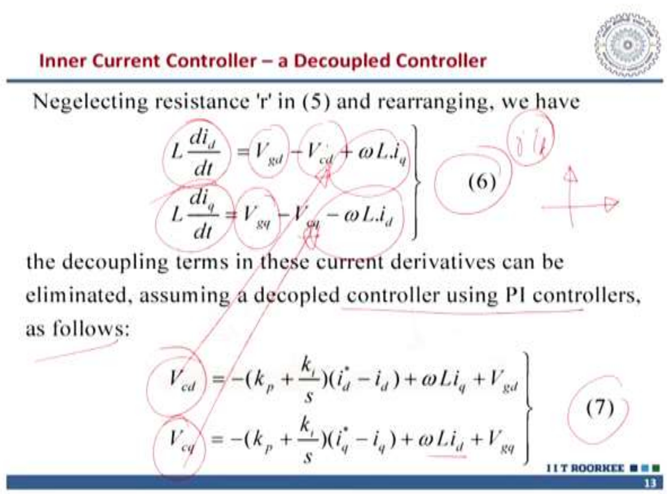

So, what happens? So, you got $L\,di/dt$ and there is little simplification just $r \times i_d$ is actually omitted, considering that resistance part is quite less. So, you got V_d minus the d axis component of this converter voltage plus $\omega L.i_q$. Similarly, you have the q axis component rate of change of q axis component with the inductor it equal to the q axis component of the grid, q-axis component of the voltage of the converter minus $\omega L. i_d$.

The decoupling term of this current derivative, can be eliminated assuming a decoupled controller using the PI controller as follows. So, this is something please understand that we wanted to this is the one of the problems. Basic purpose of our ‘dq’ control is to operate it which was come from the induction machine operations. Essentially, we can control the d-axis component, that is nothing but the voltage component and the flux component and, in that case, we will be independent to each other.

So, we can control speed and the torque independently. That was the main motive of the ‘dq’, but while doing that here we wanted to have a real axis component and the reactive axis component separately. But unfortunate there is a coupling term in between. How to get rid of this coupling term? That is a challenge. So, we required to decouple for the independent control and we are saying that it can be achieved by the PI controller. So, this is one of the techniques. So, $V_{cd} = -\left(k_p + \frac{k_i}{S}\right)\left(i_d{}^* - i_d\right) + \omega L i_q + V_{gd}$. Similarly, the $V_{cq} = -\left(k_p + \frac{k_i}{S}\right)\left(i_q{}^* - i_q\right) + \omega L i_d + V_{gq}$. So, you get both the term and thus you can see that how you can segregate this term in our next slide.

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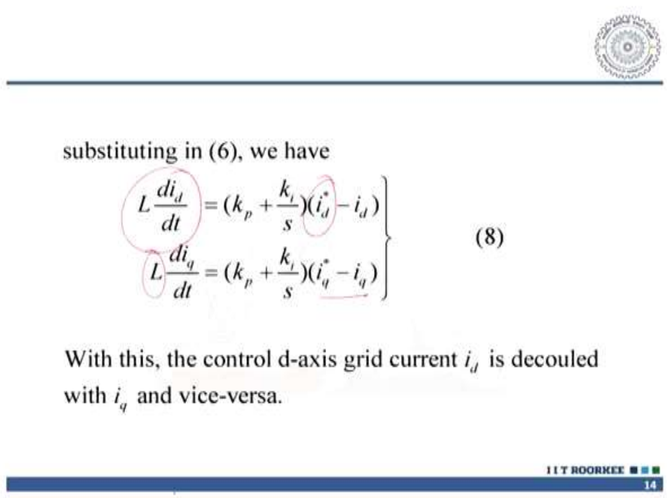

So, now this is an equation 6. So, you substitute here this term and this term.

Thus, subsequently the equation which you will get is the equation 8 with little rearrangement. So, ultimately what you get it is $L\frac{di_d}{dt} = \left(k_p + \frac{k_i}{s}\right)(i_d^{\,*} - i_d)$. Please go back to our first second slides of previous class. There we have discussed the principle of operation of the grid connected inverter. There after $L\frac{di_q}{dt} = \left(k_p + \frac{k_i}{s}\right)\left(i_q^{\,*} - i_q\right)$.

With this, we can say that the control of the d axis current is decoupled with the q-axis current and vice versa. Just choosing a proper PI controller and it is easier to operate in a dq mode because this quantity looks like DC. So, there is a no problem with the bandwidth.

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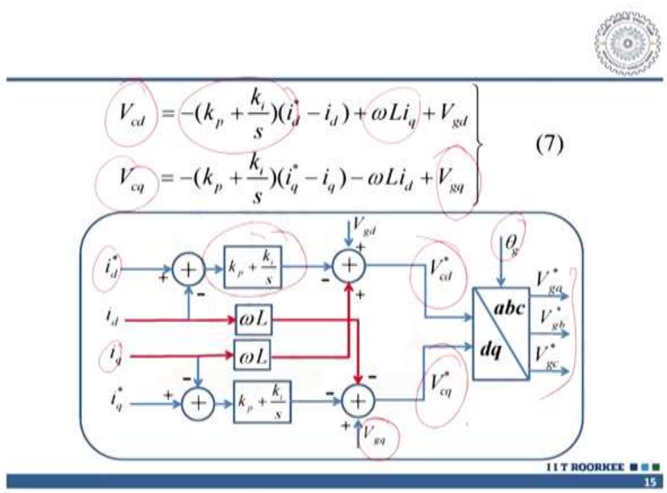

So, how this block diagram has been represented? It is a voltage. So, $V_{cd} = -\left(k_p + \frac{k_i}{s}\right)(i_d^{\,*} - i_d) + \omega L i_q + V_{gd}$.

Similarly, it is $V_{cq} = -\left(k_p + \frac{k_i}{s}\right)\left(i_q^{\,*} - i_q\right) + \omega L i_d + V_{gq}$. So, i_d^* minus i_d. You can subtract. There after you feed to this PI controller. This is this PI controller and ultimately you have to subtract with this sum with the V_{gd} and ultimately essentially what you get? It is the reference component of the dc of this converted voltage in d axis.

Similarly, if you have i_q and i_q^* and you subtract and from this subtraction you get this term. There after you subtract with the V_{gq} and thus what you get essentially your V_q reference. You convert with the abc to dq frame. Essentially you get the grid voltages for the abc frame of reference. This is a way to control your grid connected voltage source converter.

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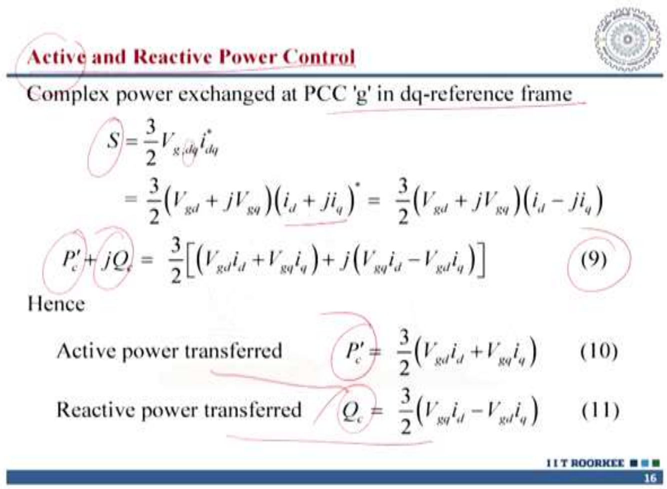

Now, active and reactive power flow control. That is quite important. Because you know you may be charging the battery. Once you are charging the battery you are charging current has to match the thermodynamics of this battery. There is a trickle charging mode there is a constraint charging mode, there is a constant voltage charging mode. Essentially, we require to see that if you are putting more current, then whether it is converted to the heat or the thermodynamics of this battery. It is essentially a chemical process is very enhanced or you require to send back the power because you have a limited capability from sending back the power from the grid to the grid or you have an energy surplus.

So, you can keep that energy which you have a surplus only. But grid itself is infinite if you try to send the power. For this reason we require to control the real power, as well as you require to inject the power in a certain power qualities because you are allowed to inject power at 0.95 perfect but you are not allowed to inject in any other power factor and for this reason we require to control active and the reactive power.

So, complex power is been exchanged because it has a both the component in dq frame of reference and that complex power or the apparent power. We can write that is the 3 by 2 V_g, that is a voltage dq into i_{dq}^*. So, if you split or expand. So, you got $\frac{3}{2}(V_{gd} + jV_{gq})(i_d - ji_q)$. From there we can split the real and the reactive part of the power. So, it is $\frac{3}{2}[(V_{gd}i_d + V_{gq}i_q) + j(V_{gq}i_d - V_{gd}i_q)]$. So, that becomes equation number 9.

So, active power transferred here it is PCC prime equal to $\frac{3}{2}(V_{gd}i_d + V_{gq}i_q)$. That becomes equation number 10. Similarly, this expressions for the reactive power component that is $\frac{3}{2}j(V_{gq}i_d - V_{gd}i_q)$. So, this is the equations. So, this is the reactive power required to be transferred and this is a real power required to be transfer of active power equal to be transferred.

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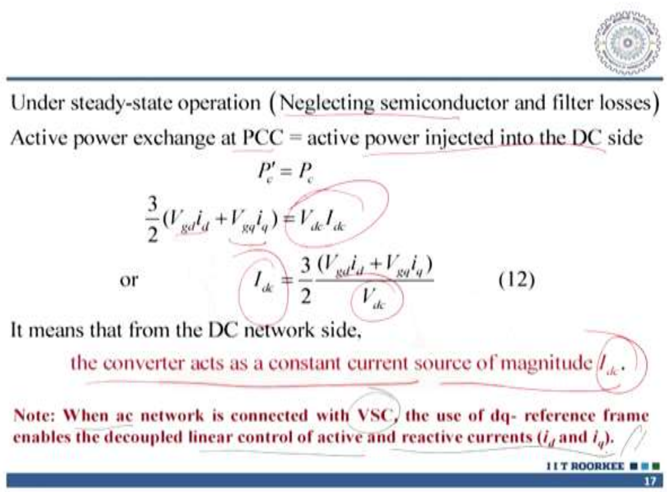

So, what we can say that under steady state conditions and we assume that these losses are neglected, semiconductor losses are neglected, filter losses are neglected. So, active power exchange at PCC that his point of common coupling equal to active power injected into the DC side of the PCC and thus $\frac{3}{2}(V_{gd}i_d + V_{gq}i_q) = V_{dc}I_{dc}$ need to me maintained. Thus, I_{dc} value should be equal to $\frac{3}{2}\frac{(V_{gd}i_d + V_{gq}i_q)}{V_{dc}}$.

It means from this DC network, the converter acts as a constant current source of magnitude I_{dc}. So, this is something we can conclude and moreover what you can note here? So, here the AC network is connected with the voltage source converter. The use of the reference frame enables the decoupled linear control and active reactive component of i_d and i_q. So, we can actively control the value of the i_d and i_q.

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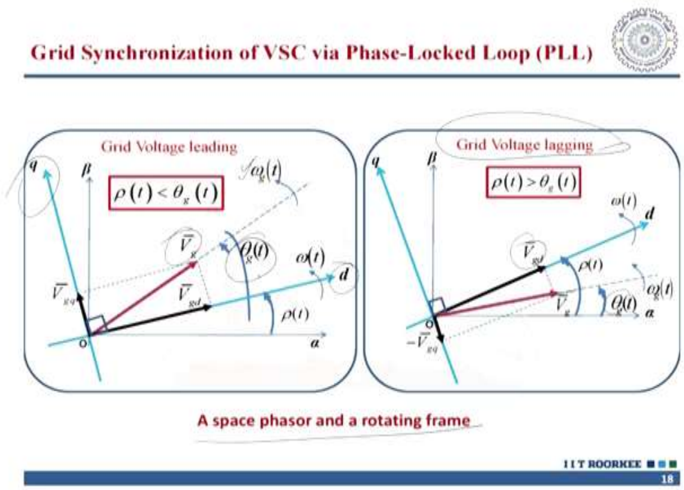

So, another interesting entity. We have shown several times in parks transformation that abc to the dq frame that you require to generate the ϴ.

That comes from the Phase Lock Loop or PLL. So, what is PLL and how does it work? That is something we are silent. So, let us discuss about this PLL in the sections here. So, ultimately you know this is your d-axis component and this is your q-axis component and with respect to 'αβ' component you got an angle maybe the ρ(t). Where ρ(t) is greater than (ϴ)g and whereas, this is the grid voltage. With grid voltage with that d axis, generally 'a' and 'd' are been aligned. You got a angle ϴg if the ρ(t) is less than ϴg, we say that that grid voltage is leading.

Whereas, if reverse happened you know this value is the ϴg, this is 'α' and this value is V_g and this value is the d axis component of the grid voltage and where ρ(t) is greater than ϴg. We call that grid voltage is lagging and this is called the phase phasor of the rotating frame of reference.

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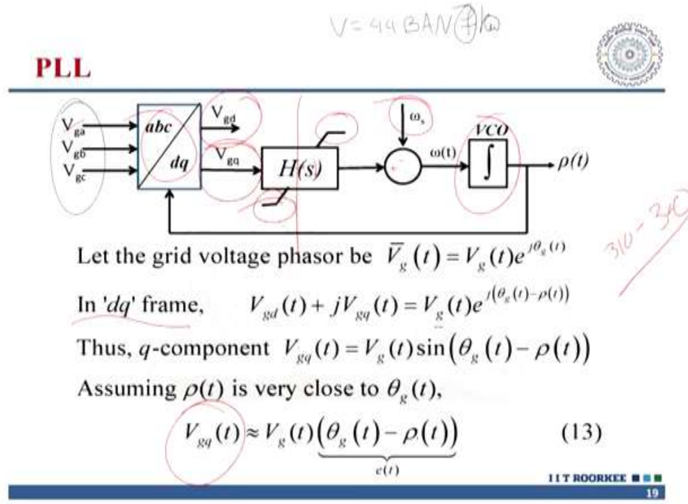

Now, how we do that? How we will calculate the Θ? It is quite simple you know. What are the equations of your voltage? Voltage equal to some constant 4.44 that there after you got flux density plus A into N into 'f' right and there the winding constant may be kw or something.

So, what you require to do? Essentially the frequency, if you integrate you get the Θ very simple thing it is. So, Θ is dimensionless. So, it is frequency of the dimension of $1/t$. So, we require to integrate it. For the three phase three wire system generally, we can generate one of the phases by subtracting. You may not take the one of the phases here. So, here you have any of the phase you can take it and you go for the Park's transformations. But how you will generate the Θ or 'ρ'? So, essentially you try to aligned your 'a' phase of the grid with the 'd'. That is a convention and ultimately you feed the 'gq' into the high gain proportional controller. Mostly this one, this is called compensator because after some value 'ω' has been limited to some value.

It cannot be more than for the 50 Hertz cycle. We have some kind of tolerance. You know that omega is 314 plus minus 5 Hertz or 6 Hertz something like that. So, maybe actually 310 to 320, in between you can keep this proportional band and but this band is quite steep. Ultimately if you can see that it is generally a 50-degree curve, 45-degree curve.

Now you subtract this value. This is essentially a mapping. What is the value of the 'q' you are getting? You will map it to the frequency ranges to the 310 maybe to 32.

Considering that 50 Hertz and you have a around 314 as a midpoint value. So, you subtract with the ωs and whatever is your generations. So, this is essentially what? Very simple, a unit voltage template.

So, that has to match and ultimately you integrate the value and it is called a voltage control oscillator and thus what you will get? This will give the feedback to conversion. if it matches, then 'a' and if you go back to the slides you know then this will not have a lagging problem. Ultimately, this 'g' and this 'd' will merge together. This is the purpose of this PLL.

So, this dq frame $V_{gd}(t) + jV_{gq}(t) = V_g(t)e^{j(\Theta_g(t)-\rho(t))}$. Thereafter same for the q axis component. Thus, it will be a sine component, $V_{gq}(t) = V_g(t)\sin(\Theta_g(t) - \rho(t))$. Similarly, we can write that $V_{gq}(t) \simeq V_g(t)(\Theta_g(t) - \rho(t))$ by the unit voltage template. That is nothing about a e(t).

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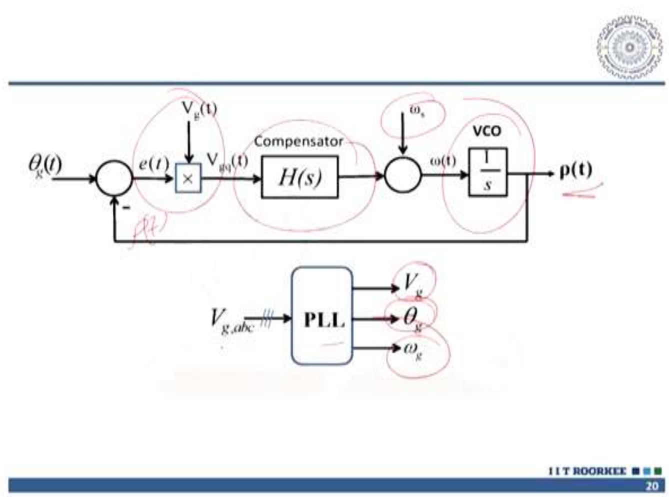

So, the error is e(t). So, that is the ρ(t), e(t), you multiply with $V_g(t)$ that gives you the q axis voltage and you have got a compensator. That is basically maps the voltage into the frequency. So, that error represents the voltage. You subtract with the unit voltage template and you feed it to the integrator. Because I told you that if you integrate, ultimately you get the Θ.

So, this is the working principle of the PLL. So, you got a $V_{g,abc}$ PLL, you get V_g, you get tϴ as well as the frequency. So, this is something you can get from your PLL.

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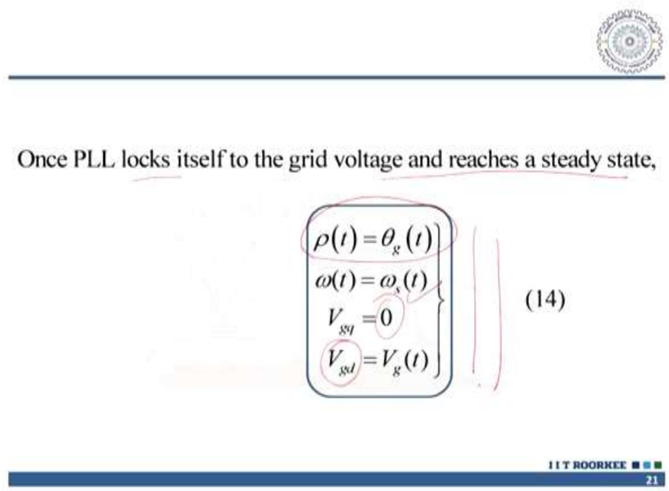

Now, once this phase lock loop itself grid voltage reaches the steady state. So, that is the oscillation. It will be there initially and then what happened? That is what I was saying that ρ(t) equal to g(t) and ω estimations will be equal to ω of the system. Since, you have totally aligned your d axis component to the a-axis component. Thus, there is no q axis component in the voltage. So, for this reason your 'gq' value will be 0 and thus your 'gd' value will be equal to g(t). This is a way it will be converging in case of the PLL.

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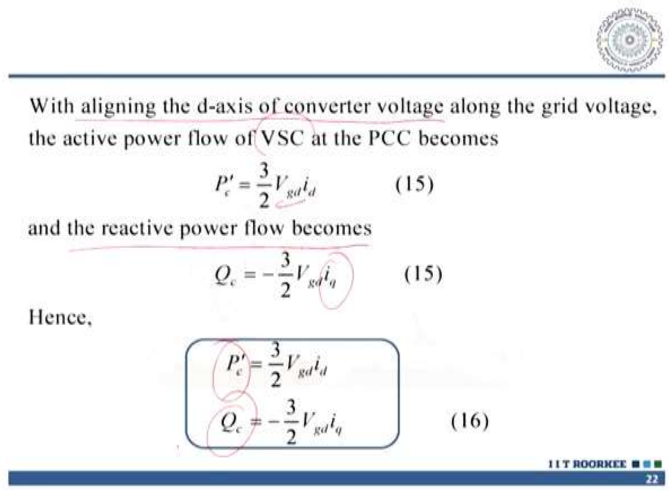

So, going back to the discussions again. So, this is the way of PLL works, but it will work when your voltage is healthy. So, if there is an issue with the unbalanced. You got a positive as well as the negative sequence component of the voltage. Then you require to do something else to estimate the PLL.

If time permits, we will discuss in detail about those PLL, but let us take a elementary example of it and proceed like that. With aligned the d axis converter voltage along the grid voltage, the active power flow of voltage source converter of the PCC, of course it becomes $P_c = \frac{3}{2} V_{gd} i_d$ that is the real part of the component.

The reactive power flow will be equal to $Q_c = -\frac{3}{2} V_{gd} i_q$. This will be the 'cos' term, voltage will be d axis and current will be q-axis. So, we can put it like that. It is power of the converter will be $\frac{3}{2} V_{gd} i_d$ and $Q_c = -\frac{3}{2} V_{gd} i_q$. So, this will be the concept.

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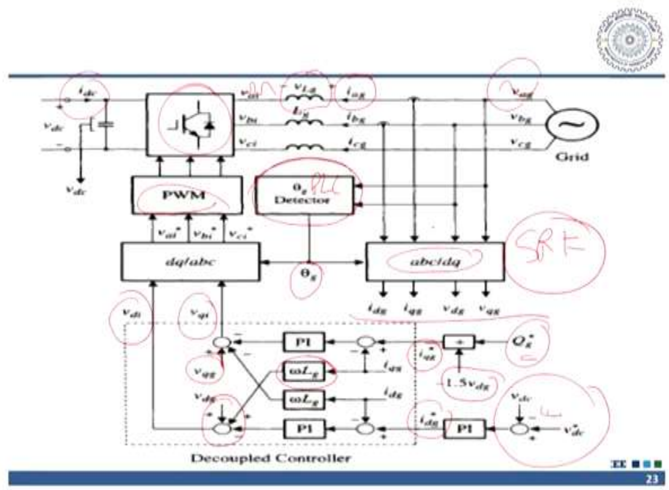

So, let us see that overall block diagram of it and it is applicable for D-STATCOM, it is applicable for the active power filter, it is applicable for or active rectifier and also solar inverter in case of the micro grid. So, this all can be tackled into the single block diagram and this mode of control is called a SRF mode. So, ultimately if you have a real source then i_{dc} will be sinking. So, assume that you got a real source and you can feed the power to the grid.

You are maintaining the value of the V_{dc} here and this is the converter. Ultimately, you got the value of v_a, v_b, v_c and thereafter you got an inductor because it is a PWM pulses here and here you got a sinusoidal waveform. So, you cannot couple them together and due to that you require to connect an inductor in between. After that this grid current becomes the a i_{ag}. Similarly, i_{bg}, i_{cg} and this is the detector of this PLL. Ultimately you can write the PLL from these three voltages, you can detect.

From there, you got the Θg because ρ will be equal to Θ when you have a balance system. So, you will convert this voltage and current because you can see that you have taken two voltages and two currents because it is a three phase three wire system and you know that v_a, v_b, v_c equal to 0. Similarly, i_a, i_b, i_c equal to 0.

So, you got i_{dg}, i_{qg}, V_{dg} and the V_{qg}. These are the four signals and ultimately you have a reference 'q' and you will have a reference V_{dc}. From there you got a difference i_{qg} and that will be subtracted here with a PI controller and there is a ‘cos’ term as I have told you in the previous case.

So, it will be multiplied and it will be dealing with the d-axis component. Similarly, there we have d-axis component, it will be multiplied with the i_q and will be dealing with the q axis component. So, it becomes a V_{qg} and this becomes your V_{dg} and this signals will be fed to the inverter or the convertor depending on the mode of operation to the V_q and it will be converted to the abc to the dq frame and thereafter you have a PWM controller to feed them to track the reference so that the whatever and there we have different mode of operation. If you find that there is a sag in the DC was voltage or swell in a DC bus voltage then this loop comes into the picture.

Otherwise, you know you can see that it is a ‘qg’ control and this is applicable mostly in the active power filter or the D-STATCOM operation. This is a SRF method of control of the D-STATCOM or the SRF.

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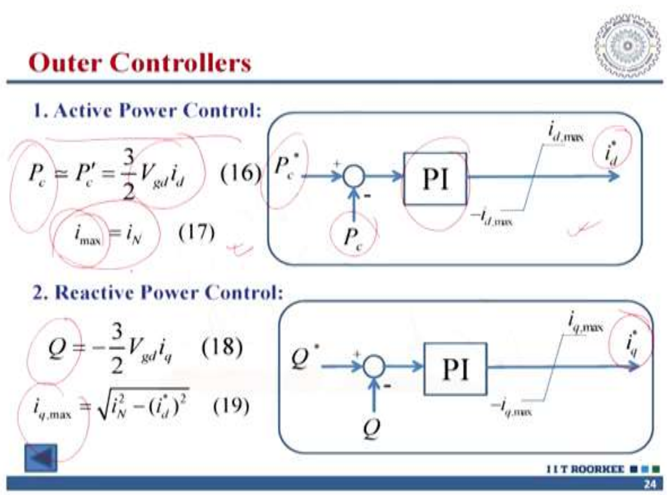

So, there is the outer controller. This was the inner controller and this will control the your active power. You know that active power P_c. We neglect the losses that is something we require to if you do total modeling then you require to take the losses. So, it is $P_c' = \frac{3}{2} V_{gd} i_d$.

Similarly, you have the $i_{max} = i_N$. So, what is the maximum value of the i_d which were allowed. Because you are choosing a devices and device has its maximum current limiting rating. Otherwise this protection circuits will come into the picture to stop the operation and for this reason this value is that let us say $i_{max} = i_N$.

So, you have a $P_c^* - P_c$ from there you got a PI. So, you have got a i_{max} and i_{mean}. From there you got i_d' and similarly you have a reactive power control and that is mostly important because this was required for the active rectifier and other mode of operation. But in case of the shunt active power filter of the D-STATCOM this loop is generally absent. So, active power control. So, it is $-\frac{3}{2}V_{gd}i_q$ and thus $i_{q,max}$ will be definitely is the square root of this and from there you will be calculating the i_q^*.

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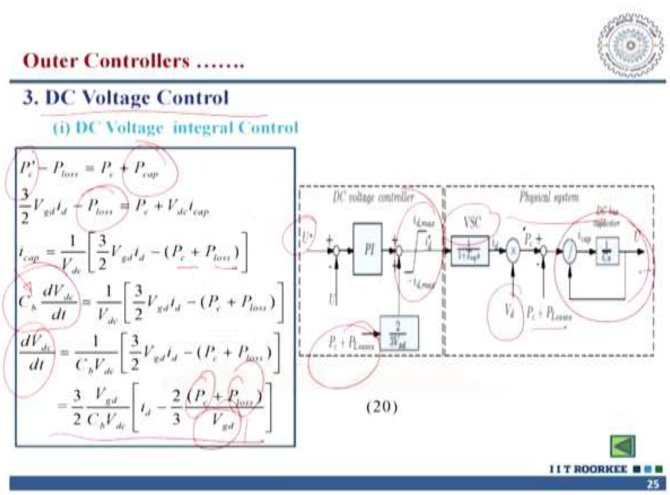

So, this is something you require to remember this. First calculate the i_d^* and thereafter from the power rating, we require to calculate the i_q^*.

So, now we have a DC voltage control. DC bus required to be maintained at some voltages and for this reason we required to have a control. So, it is P_c' equal to minus P_c loss equal to P_c plus the capacitor power because there is an ECS and other issues. So, for this reason real power required to be feed into the capacitor to maintain its dc bus voltage. So, thus 3 by 2 'V_{gd}' into i_d minus the losses of the switches and the capacitor parasitic everything= $P_c + V_{dc}i_{cap}$. So, $i_{cap} = \frac{1}{V_{dc}}\left[\frac{3}{2}V_{gd}i_d - (P_c + P_{loss})\right]$.

So, from there what we can say is that the $C_b \frac{dV_{dc}}{dt}$. This is basically nothing, but a current $C_b \frac{dV_{dc}}{dt} = \frac{1}{V_{dc}}\left[\frac{3}{2}V_{gd}i_d - (P_c + P_{loss})\right]$ and previously we have neglected the loss component here we have added to the loss component otherwise you will find that DC bus voltage is sinking. So, $\frac{dV_{dc}}{dt}$ equal to, C part will come here. Ultimately this is the expression. This is nothing but a ripple. The rate of change of volt DC bus voltage is nothing, but a ripple. So, it is $\frac{3}{2}\frac{V_{gd}}{C_b V_{dc}}\left[i_d - \frac{2}{3}\frac{(P_c+P_{loss})}{V_{gd}}\right]$.

So, this will be the expressions of the ripple and you generally designed with a permissible limit because you know that what is the power of the converter. What are the losses? You should estimate or calculate and you know the grid voltage. So, there is a problem you know. If there is a voltage sag the ripple will be more. So, for this reason we required to have a; please go back to the circuit. Please go back to this controller. You have extra voltage control DC voltage control loop if there is a voltage sag.

So, this is the case you have V_{dc}^* minus V_{dc} you feed it to the PI control and this part is essentially the losses that is this value and then you subtract it, you add up and within that you can have a $i_{d,max}$ and $i_{d,min}$. Generally, we calculate by putting everything in a PI controller and try to do that. So, ultimately you left everything to the tuning of the PI controller.

But this is a quite blind operation and for this reason I suggest the go by this way and this is a physical system. This is a power flow. This is a voltage source converter and there is a delay for this reason it has been incorporated by 1 by 1 plus equivalent switching of the timing. That will give you i_d. There after you got a V_d, you got P_c. This is a loss. Ultimately you got a $i_{cap} \frac{1}{C_s U}$. So, this is a way of power flow in case of the DC part of this voltage source converter.

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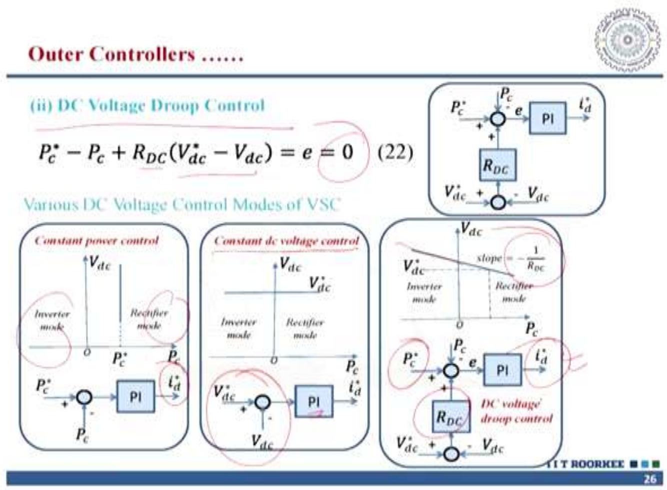

So, let us recap what we have said. This is called the voltage droop control. Sometime it is very much useful because once you find that voltage is drooping that is not applicable only on power quality issues, but also in case of the distribution system, especially we are talking about DC micro grid. They are featured in a long way. So, $P_c{}^* - P_c + R_{DC}(V_{dc}{}^* - V_{dc}) = 0$. Then you say that you are maintaining a constant voltage.

Now, this is the inverter mode and this is a rectifier mode and you have a $P_c{}^* - P_c = i_d{}'$. Similarly, if you want a constant dc voltage control you require to maintain the receivers. We generally do that in case of the shunt active power filter. So, it is $V_{dc}{}^* - V_{dc}$ and from there you got a PI controller that is i_d. This is called a constant voltage control method and sometimes we maintain that.

Sometimes we go for the droop control. What happened? You have inverter mode their voltage goes up and you got a rectifier mode is generally power feed in and thus you got a resistance of this R_{DG} and you require to operate in that mode. This is the control of the power and this is actual reference power of the converter. It is actual power of the converter that will be the difference of ‘e’, that will be fed into the system. That is $i_d{}^*$

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Direction of the i_d^* will depend on whether you are operating in a converter mode or the inverter mode and you got R_{dc}. There after you have ${V_{dc}}^* - V_{dc}$ and it will be divided rather by R_D and ultimately, you will be calculating the value of the i_d^*.

This kind of control is a droop control method and this is followed in mainly DC micro grid kind of system. Where power flows through or takeaway through the front-end active converter. But power quality plays an important role because once you are taking power from the grid, you cannot throw the garbage into the system. Also, once you are injecting power from your power surplus from the micro grid to the main grid then also you required to inject the quality power.

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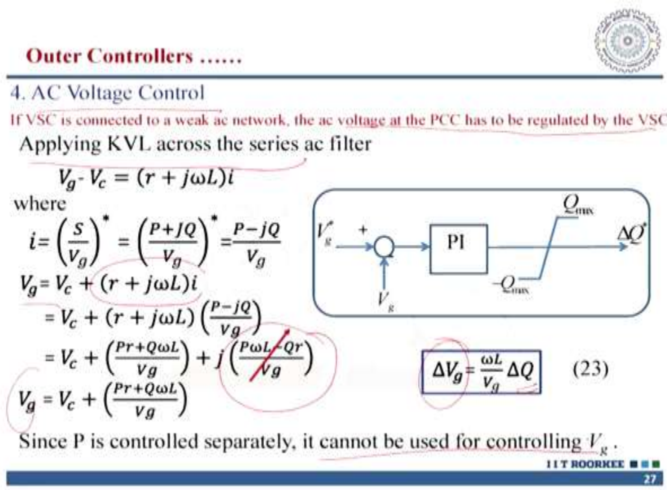

So, let us see that this is an AC voltage control and if distributed network is a weak network and the AC voltage has to be regulated by the voltage source controller, then instead of the grid, it is a rigid body. So, we have to apply the KVL and ultimately you have the current that is basically your voltage by the apparent power.

So, $V_g = V_c + (r + j\omega L)i$and from there $V_g = V_c + \left(\frac{P_r + Q\omega L}{V_g}\right)$ because this part is required to be nullified. So, because we want that 0 reactive power to be supplied and thus the change of the grid voltage will be $\frac{\omega L}{V_g}\Delta Q$. So, in that way the reactive power will be injected.

Since, P is controlled separately, it cannot be controlled the V_g. That is the one of the problems. So, we know that in frequency reactive power control comes from the excitation and the real power control comes from the speed of the generator since same thing here. Since P is controlled separately, it cannot control the V_g. It has to be controlled in a different mode. For this reason we required to have a frequency support of the AC micro grid.

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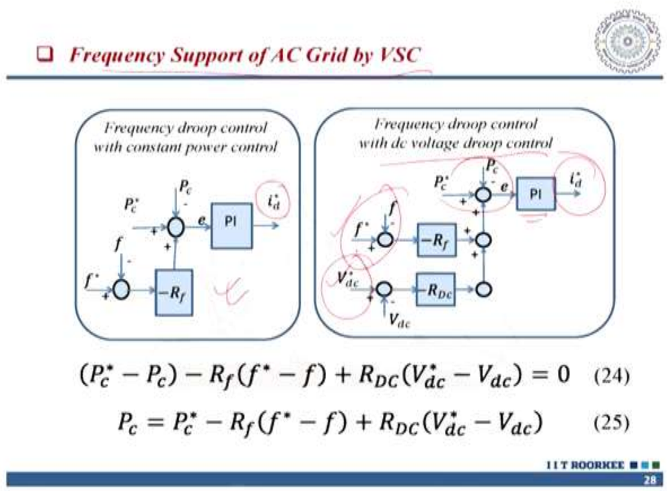

So, here we have a droop control and thus we can control the frequency here and, in that way, this is the reference current and this is the frequency droop control and generally it has been used in the micro grid in detail. Frequency droop control with the DC micro grid control, we can have this two coupled. This is the V_{dc} where DC bus voltage is required to be maintained and your frequency droop and both will put into this place and there is a PI controller and this way this will be the i_d reference. i_d reference will stabilize both this drooping features.

In that way, voltage source converter also can be used for the mitigation, of the frequency as well as the voltage drooping. Thank you. Thank you for your attention. I have almost covered everything that I have tried to cover in a detail. That is the features of the grid connected voltage control converter and its control. We shall look forward to its applications in power qualities.

Thank you.