

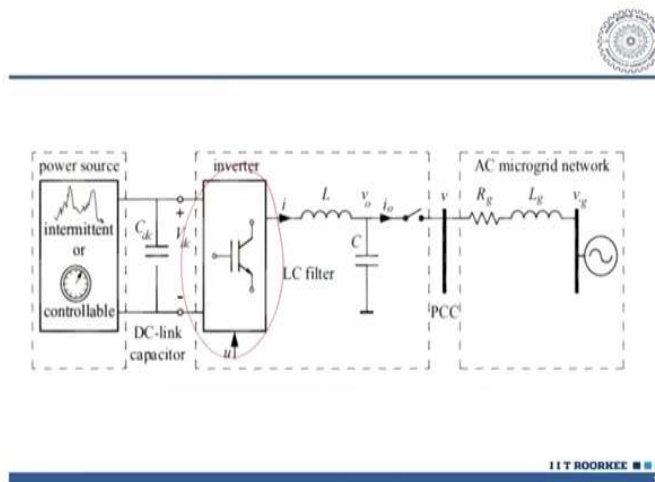
Power Quality Improvement Technique
Prof. Avik Bhattacharya
Department of Electrical Engineering
Indian Institute of Technology, Roorkee

Lecture - 27
Operation and Control of Grid Connected VSC

Welcome to our NPTEL courses on the Power Quality Improvement Technique. Today we are going to discuss the Operation and Control of this Grid Connected Voltage Source Converter. This discussion is not restricted to the power quality, because shunt active power filter or the D-STATCOM essentially is the grid connected inverter.

Nowadays with a penetration of the solar inverter and other entities, we have coupled a power quality issues with a distributed generation and for this reason we require to have a heuristic discussion of this operation and the principle of operation of the voltage source grid connected voltage source inverter.

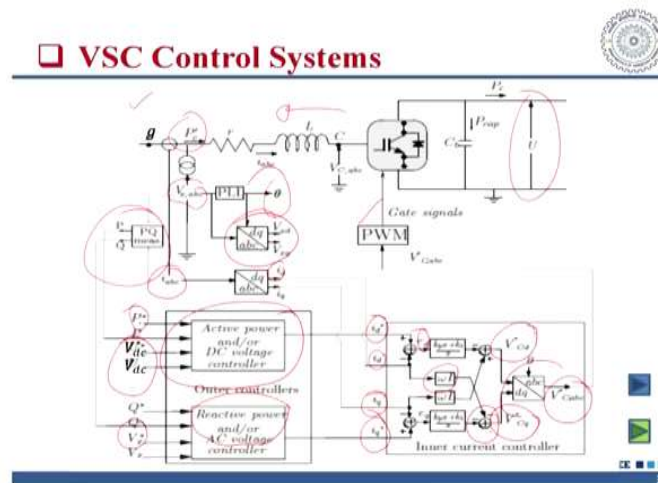
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You know what happened there now? This topology can act also as a shunt active power filter at the point of common coupling. So, filters are required to be little higher side for the actively use as an active power filter and it can be coupled with the distributed generation like solar and other entities mainly.

So, then it can have a power to compensate the reactive power compensation. Apart from the reactive power composition, it can composite the real power. This kind of integrated topology is gaining advancement and it has been distributed generation and the power quality both these issues are been integrated and it looks like an integrated problem nowadays. How it is been done let us see?

(Refer Slide Time: 02:18)



Generally, what happens? This is your grid point and we say that it is a PCC and if you wish to inject a certain amount of the reactive or the active power with the present of this active source in the DC link then you have to have a P Q control. What happens then? We have talked a several time this. PLL generally this point is called a point of common coupling and from there you have a PT generally. This will measure the voltage and from there essentially you will generate the 'Θ'. That is very important component and also, we want that to transform all the quantities into the 'dq' frame.

What is the 'dq' frame? You know very well that, from three-phase system a b c you go to the 'αβ' frame. This is nothing, but a three force to resolving into the 'x' 'y' coordinate that is the 'αβ'. When 'αβ' is rotated at the synchronous speed or the frequency that is generated by the PLL and instantaneous position is generated by the 'Θ' also. Then this frame of reference. Then the fundamental component looks like a DC parameter. Then tuning of the PI controller and other issues become easier and for this reason we have told

several times that, basically an SRM method to convert into the 'a b c' to d q frame of reference.

Now, see that this is the P Q reference technique. Then you have P^* from their reference. You may know that from the iteration and all those things. You may know that. You required to supply certain amount of the real power to the system. If it is not present, then P^* can be zero. Ultimately you require to sink certain amount of power from the grid to maintain the DC link voltage and there after you will have DC^* and DC.

This is your active power controller. Similarly, you have a reactive power controller. Generally, this is been used frequently for the D-STATCOM. So, you required to inject a certain amount of the reactive power. You got a Q^* . An actual Q will be measured from this current and voltage.

You also check that this voltage at this point is healthy or not. If it is healthy, or in the length of the tolerance, then V_x is the voltage at the point of common coupling. It is sagged or swelled. Then this value will be different and ultimately what happened? You got this a b c from there you got a d q and you from this P and P^* V_{dc} and the V_{dc}^* these are the real power component and ultimately you will generate that i_d^* .

Similarly, actual i_d measured after transformation will be this and this been subtracted. There after you will feed this error into this PI controller and same way there will be a 'cos' term. So, 'd' will be multiplied by the ' ωL ' and will be subtracted from 'q'. But both are the subtraction that ultimately the addition and similarly, this 'q' reference what has been generated from voltage sags and the reactive power compensation Q^* has been generated and that will be subtracted from the i_q .

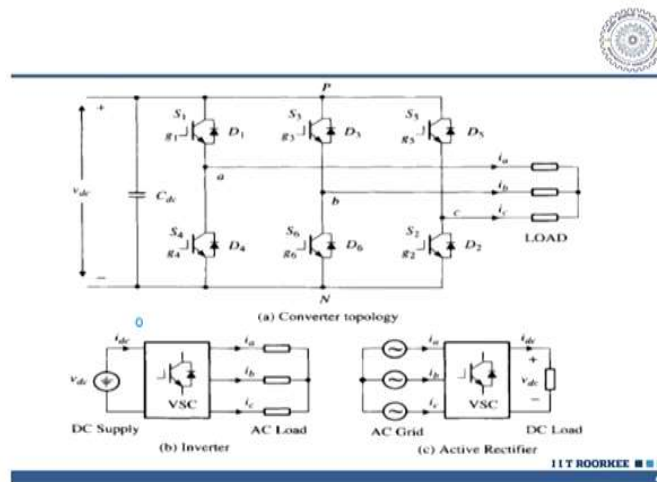
Again, it will be multiplied by ' ωL ' and that will be again added up. With that ultimately this will be the V_{cd} . The reference voltage after compensations and similarly, by multiplying ' ωL ' and you add up this component. These both will be minus sign and thus you get V_{cq} .

Generally, if there is a presence of the real power, real power has to flow this way and it is minus, because reactive power required to be compensated, ultimately you have to inject the positive VAR. So, you got again from ' Θ ' and this ' Θ ' will be fade again into the d q

to a b c block. From there you will generate this control signals for the PWM. We have already discussed PWM in our discussions.

So, different kind of PWM technique can be applied depending on the level of the inverter and then it will trigger this device. This is the way to control your voltage source controller in grid connected way with active source or without active source. With active source it has a power to compensate power to inject the real power. If there is no active source this cannot inject the real power.

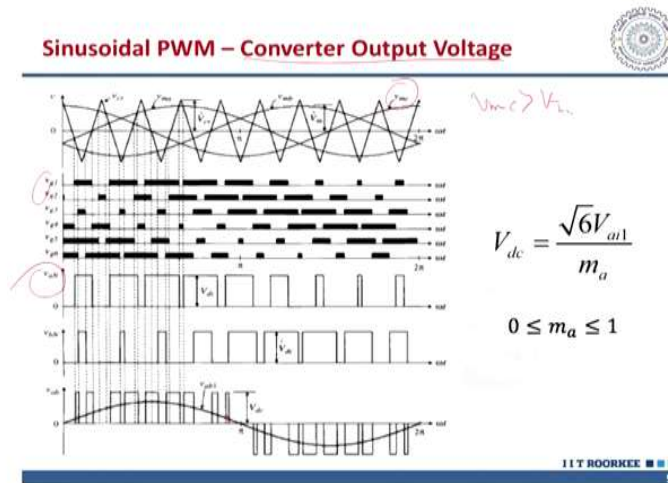
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So, if we talk about the distribution system and we may have a simplest system that is the two-level inverter. Then what happens? You may have a DC source here that may be a solar and you are feeding this load. So, it is not a grid connected entity. There it is quite easy, because then you can choose a reference and you force that current to track that reference and generally once power flows from DC side to AC side, we say the inverter operation. That is what your household inverters are.

What happens you know? When it is there when your grid is on, then you may be charging the battery. This becomes load then and ultimately you require to take power at unity power factor. Then it becomes an active rectifier and you will be charging at a unity power factor and there also you required to control the P and Q. So, it has a different mode. Once you are sending power to DC to AC, then P become positive. Here if it comes from the grid, then it becomes the load. That 'P' becomes negative.

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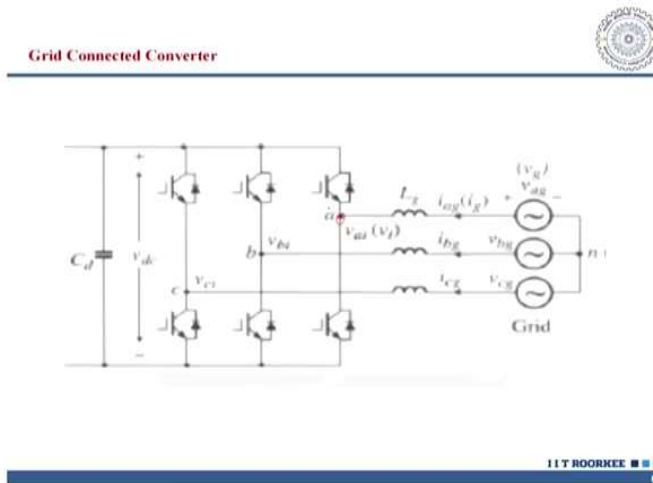


So, this is the typical sine modulation technique. We have discussed it in detail. We just not going to this again. So, this is based on this where the logic is that the modulating signal is V_{mc} . If it is greater, greater than V triangular, or V carrier, then particular phase is switched on. Based on that you have a six gate signals for two level inverter v_{g1} , v_{g2} , v_{g3} , v_{g4} , v_{g5} , v_{g6} . Accordingly pulse width duration will change and ultimately these are the phase voltages. This is V_{aN} , V_{bN} . If you add this phase voltages then you will get the line voltages and ultimately you can find that this is the line voltages of this PWM nature.

Please understand, that you require to provide an inductor. Why? Because ultimately this sine waves volt areas curve matches with this sinusoid matches with the pulse width modulated wave form. But there is an instantaneous variation between the PWM voltage and the voltage at this point.

For this reason, we required to provide a buffer inductor and thus the calculation of the L_f or the inducted side inverter and the grid side inductor comes into the picture.

(Refer Slide Time: 12:25)



Now, the grid connected inverter. So, ultimately what happens? You require to synchronize, because at this point, please go back. You can see the voltage is this. May be at peak you know. So, what happens? So, if this point voltage has some value and this point voltage have some value and you require to inject the current, because ultimately you are giving this kind of pulses.

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$$\frac{V_{te}}{\omega} = V_{s-wt} = \frac{L \frac{di}{dt}}$$

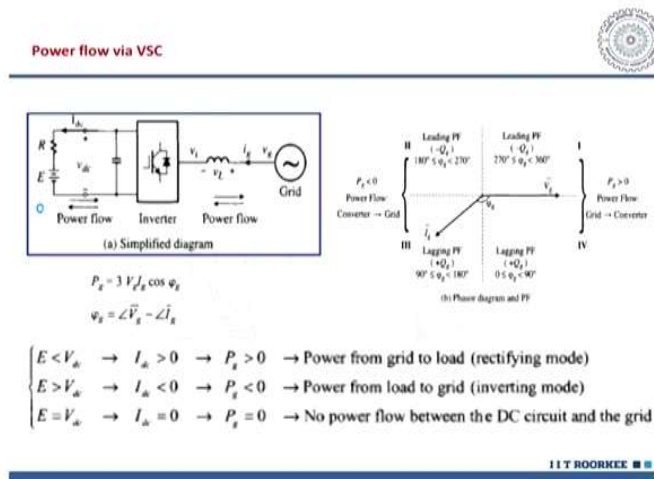
$$P_{in} = \frac{V_1 V_2 \cos \phi}{\lambda}$$

Instantaneous current definitely will be flowing depends on (let us go to the take the white board) basically when it is switched on and you get if it is half bridge converter $\frac{V_{dc}}{2} \sin \omega t = L \frac{di}{dt}$.

So, you can integrate this value and get the value of 'i' and for this is purpose of the PI controller. Ultimately you can see that injecting current has a dynamic. So, controller has to ensure the first switching. So that you want a particular sinusoidal wave form to follow and that will be followed and ultimately you required to inject a particular value of the power that is given by $\frac{V_1 - V_2}{X} \sin \delta$. So, this is something we required to control.

So, this is the way we require to control the grid connected inverter and if it acts as an active rectifier. Sometime it acts, because a you may have bulk of the batteries to be charged. So, you required to be charged in a sinusoidal fashion. It will be like this and reverse can also be true. Because you may have a peak management control especially in evening. So, you want to feed the power from this storage element or you may have a solar. Then power will flow back from the DC side to AC side.

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Now, let us see. This is the case of power flow via VSC and this is a power flow and ultimately if it is from the grid side to the inverter side. It is the active rectifier and if it is reverse then inverter operation and also there is an issues of the power factors. For

example, if P_g (that is a grid) power is greater than '0'. So, power is flowing from the grid, to the converter and that is your first quarter operation.

Generally, if it is a leading power factor, then you have the operation range of the 270 to the 360 range. On the other hand, in this coordinate, you got the P_g positive here. But you can have a negative power factor this is the angle it will vary. It is within the 0 to 90 degree.

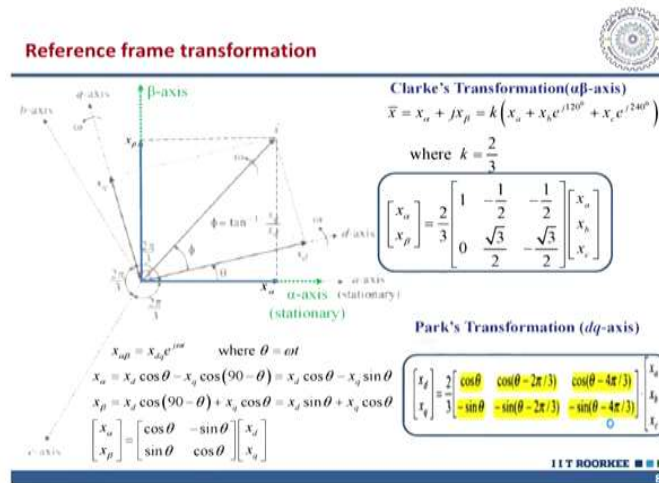
Similarly, there is a second quadrant that lies in between 270 to 180 degree and where power will be flowing back from the grid to the source and for this reason you can see that net power received by the grid and thus it is from the solar to the grid may be and you can have a this operation. Accordingly, you will fix up whether you want a leading power factor operation or the lagging power factor operation. That comes into the picture, when whether you want to have a power quality issues. That is how much reactive power you require to compensate.

See in my discussions I am silent about the harmonic power. I will be taking out this issue separately, that is shunt active power filter and that is a one of the major issues. It is in case of the power quality. So, for this reason this is the logic you know this the grid power is given by definitely for the three-phase system in terms of the phase values. It is $3V_g I_g \cos \phi_g$ can be any value 0 to 360 degree and where ϕ is the angle between the V_g and the I_g , the phase angle.

So, generally you know if this voltage V_{dc} is the voltage and it is E . That mean you know what happen very simple. That, V_{dc} voltage is more that mean it is charging the battery. So, I_{dc} is positive and thus P_g is positive and the power flow is to the grid to the load and it is a rectifier mode. Of course, you require to take a unity power factor operation. Same way if you have that ' E ' > V_{dc} , then I_{dc} is negative, definitely this value is more, definitely current is flowing to this direction and thus P_g is negative. So, it is in the inverting mode.

Maybe this is not there in case of the shunt active power filter, because it does not compensate the real power and thus this concept does not arise. But it is equal to boost up the DC bus voltage to some extent. So, $V_{dc} = E$. Then it is in a floating mode. Then $I_{dc} = 0$ and $V_{dc} = 0$. So, no power flow between the DC circuit and grid takes place.

(Refer Slide Time: 19:17)



Now, there is an important transformation as I was telling you. 'αβ' to a b c to the 'αβ' frame, this is nothing but three factors resolving into the 'x y' coordinate. We say it is an 'αβ'. Then once 'αβ' is been rotated by the synchronous frame, then it becomes the 'd q' frame of reference. So, this is the transformation. Once you have a b c coordinate, this is the pictorial represent phasor representations.

This is the a-axis stationary and we aligned 'a' with 'α' and thus you got a b-axis and you got a c-axis and it is rotating with a speed of ω. So, all the vectors you can resolve into the 'αβ' frame and by this transformation where $\bar{x} = x_\alpha + jx_\beta$. Where k is 2/3, this x_a plus x_b you have to multiply with the 120 degree and you have to multiply with the 240 degree or minus 120 degree where k equal to 2/3. So, you can get this transformation in this way.

So, alpha beta equal to, it may be voltage or current anything. So, this transformation is called the Clarke transformations and thereafter since x alpha beta can be multiplied by the synchronous frame of reference. Then it becomes the d q frame of reference that is $x_{dq} e^{j\omega t}$. Where $\theta = \omega t$ and thus $x_\alpha = x_d \cos\theta - x_q \cos(90 - \theta) = x_d \cos\theta - x_q \sin\theta$.

Similarly, you can write $x_\beta = x_d \cos(90 - \theta) + x_q \cos\theta = x_q \cos\theta + x_d \sin\theta$. Thus, the transformation from 'αβ' to d q will be this. This is a transposition matrix. Ultimately if you couple these two transmissions, you can have directly 'a b c' to 'd q' and vice versa.

If you go by reverse, then it is called the reverse Parks transformation. So, this transformation is called the Park transformation, while converting to the 'a b c' to the 'd q' frame of reference directly.

So, you got this 'k' which will come out here and you got:

$$\begin{bmatrix} \cos \theta & \cos(\theta - 2\pi/3) & \cos(\theta - 4\pi/3) \\ -\sin \theta & -\sin(\theta - 2\pi/3) & -\sin(\theta - 4\pi/3) \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

So, in this way we can compute the 'αβ' to d q frame or directly 'a b c' to 'd q' frame and if you take the matrix inverse of it, then it is called reverse parks transformation.

(Refer Slide Time: 22:59)

Control of Grid-Connected Converter

Applying KVL across PCC 'g' and converter 'c'

$$V_{g,abc} - V_{c,abc} = r i_{abc} + L \frac{di_{abc}}{dt} \quad (1)$$

Applying Clarke Transformation,

$$V_{g,\alpha\beta} - V_{c,\alpha\beta} = r i_{\alpha\beta} + L \frac{di_{\alpha\beta}}{dt} \quad (2)$$

C dv/dt →

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Now, we required to come across few terms. As I was writing in a white board that, this voltage is varying and this is a PCC and ultimately this is the power of the compensator that I am writing as C. It can be shunt active power filter. It can be active rectifier or anything else.


So, this is the lump resistance. We have not connected this resistance physically. All the resistance in series has been lumped out here and this is the inductor connected into the circuit. So, what happens? We can read out these equations for current source and the capacitor. In case of this solar model it fits quite well or you know that why it is so, because ultimately $C \, dv/dt$ is essentially gives you the 'P'.

So, 'I' we can write where voltage dependent current source or solar is also same thing. Anyway, for this reason we have put it as a dependent current source and capacitor. Thereafter you got I_{DC} . So, if you combine these two parts, this is the AC part. If you go by essentially this part this part is your DC part and this part is AC part. Just we have replaced it like this. This part is AC part, this part is DC part.

So, applying KVL across the PCC this we write as a 'g' and 'c' as a converter. So, this is a single notation representation, it can be $V_{g,abc} - V_{c,abc}$. There after this is the resistance part of it. There after inductor part of it and by having a Clarke transformation we can put this equation into the ' $\alpha\beta$ ' frame. That is your $V_{g,\alpha\beta} - V_{c,\alpha\beta} = ri_{\alpha\beta} + L \frac{di_{\alpha\beta}}{dt}$.

Then we go for the parks transformations and convert into the d q frame of reference. Then $V_{g,\alpha\beta} = V_{g,dq}e^{j\omega t}$, $V_{c,\alpha\beta}$ equal to this compensated or the converters voltage d q frame of reference $V_{c,dq}e^{j\omega t}$ and where this current in ' $\alpha\beta$ ' can be transformed to d q by $i_{dq}e^{j\omega t}$.

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With Park's Transformation,

$$\left. \begin{aligned} V_{g,\alpha\beta} &= V_{g,dq}e^{j\omega t} \\ V_{c,\alpha\beta} &= V_{c,dq}e^{j\omega t} \\ i_{\alpha\beta} &= i_{dq}e^{j\omega t} \end{aligned} \right\} \quad (3)$$

substituting in (2)

$$\begin{aligned} V_{g,dq}e^{j\omega t} - V_{c,dq}e^{j\omega t} &= ri_{dq}e^{j\omega t} + L \frac{d(i_{dq}e^{j\omega t})}{dt} \\ &= ri_{dq}e^{j\omega t} + j\omega L i_{dq}e^{j\omega t} + L \frac{di_{dq}}{dt}e^{j\omega t} \end{aligned}$$

Dividing all terms by $e^{j\omega t}$,

$$V_{g,dq} - V_{c,dq} = ri_{dq} + j\omega L i_{dq} + L \frac{di_{dq}}{dt} \quad (4)$$

IIT ROORKEE 10


So, substituting this equation in equation '2'. So, essentially get the equation into the d q frame. So, it is $V_{g,dq}e^{j\omega t} - V_{c,dq}e^{j\omega t} = ri_{dq}e^{j\omega t} + L \frac{d(i_{dq}e^{j\omega t})}{dt}$. Mind it I told you that AC parameter, in d q frame looks like DC parameter. But it is a transformation.

So, these quantities are time varying. Please note that and for this reason this differentiation exist. So, I have been asked several times by the students, "sir once you are operating in a

d q frame, so how this parameter preserves? Because it looks like DC". But do note that, these quantities are essentially are the time dependent. So, differentiation exists.

So, $ri_{dq}e^{j\omega t} + j\omega Li_{dq}e^{j\omega t} + L \frac{d(i_{dq})}{dt} e^{j\omega t}$. Ultimately you divide both side by $e^{j\omega t}$. So, you get the equations incase of the d q frame of reference. That is . So, this is the equations $V_{g,dq} - V_{c,dq} = ri_{dq} + j\omega Li_{dq} + L \frac{d(i_{dq})}{dt}$.

(Refer Slide Time: 28:01)



expanding the terms
$$\left. \begin{aligned} V_{g,dq} &= V_{gd} + jV_{gq} \\ V_{c,dq} &= V_{cd} + jV_{cq} \\ i_{dq} &= i_d + ji_q \end{aligned} \right\}$$

substituting in (4) and rearranging, we have

$$\left. \begin{aligned} V_{gd} - V_{cd} &= ri_d - \omega L i_q + L \frac{di_d}{dt} \\ V_{gq} - V_{cq} &= ri_q + \omega L i_d + L \frac{di_q}{dt} \end{aligned} \right\} \quad (5)$$

◀ Cross-coupling of d- and q-axis terms creates problem in power control.

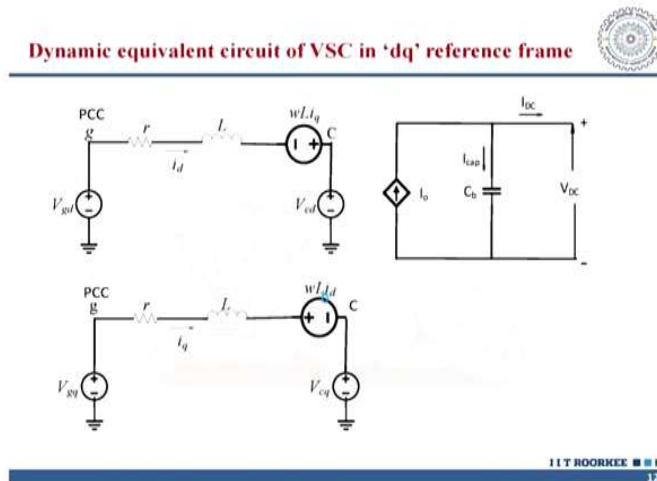
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Now, expanding this term you know. V_g is essentially we can write it is d-axis component and to show that quadrature axis component is at 90 degree. So, you have multiplied with the g. Similarly, for the converter voltages $V_{c,dq} = V_{cd} + jV_{cq}$ similarly $i_{dq} = i_d + ji_q$. Substituting the 4 and rearranging them $V_{gd} - V_{cd} = ri_d - j\omega Li_q + L \frac{d(i_d)}{dt}$, and thus $V_{gq} - V_{cq} = ri_q - j\omega Li_d + L \frac{d(i_q)}{dt}$.

So, this is the equations you will get in case of the control loop and you know these are coupled equations. Because I have shown in your please go back that, you know I once I have shown this control algorithm here. So, here there is a 'cos' term. You have multiplied with the ω and you have added up. So, this is your ' ωL ' and this is the 'cos' term had been added.

So, similarly this is your 'cos' term being added. For this reason, you know, this is the q axis equations but there will be a term of i_d and this is a g-axis this is the d-axis equation. Ultimately you will have a 'cos' term with a minus sign.

(Refer Slide Time: 30:05)



So, then we have the dynamic equivalent of the voltage source converter in the dq frame of reference. So, instead of a b c you have just only three parameters. This is the DC side that has no change. But in AC side you have this is your 'v' grid voltage in that d-axis. Thereafter resistant it does not change. You got an inductance that is L.

Now, you have an extra term that is a voltage. You see that the polarity will be different for the different voltage. Here this one is negative and this one will be positive and for this reason, you will have ' ωL ' i_q negative, and here it will be your positive. So, this is a representation for our case, for this 'dq' representation.

Thank you for your attention. We shall continue to the grid connected inverter in our next class.