DC Microgrid and Control System
Prof. Avik Bhattacharya
Department of Electrical Engineering
Indian Institute of Technology – Roorkee

Lecture - 17
Microgrid Dynamics and Modeling (Continued)

Welcome to our lectures on DC Microgrid and Control System. Today we shall discuss about microdynamics of this microgrid dynamics and its modeling.

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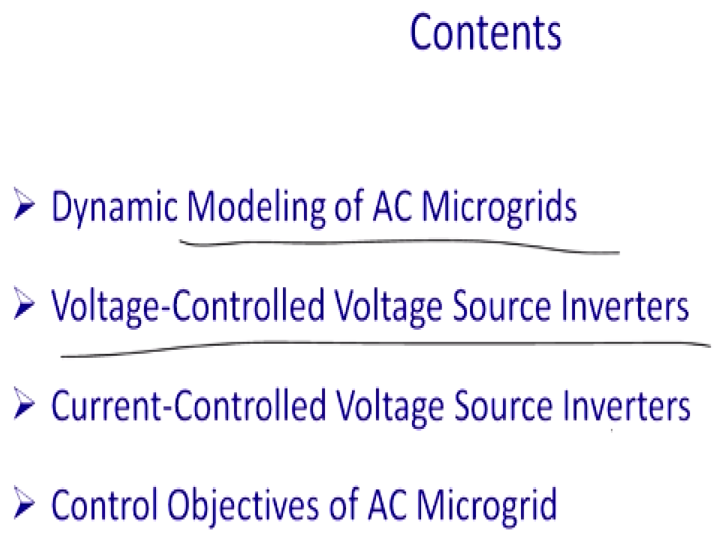

So, our content of this today's lectures will be dynamic modeling of AC microgrid that we require to understand because there is some portion of the microgrid might be the DC, so we shall also take the modeling of the AC microgrid and then we shall see that what are the changes of the AC microgrid and the DC microgrid. So, voltage-controlled voltage-controlled voltage source inverter, we shall see that how it will be designed.

Thereafter, current-controlled voltage source inverter and then control objective of AC microgrid will be discussed.

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Dynamic Modeling of AC Microgrids

- The microgrid control schemes employ the nonlinear dynamical model of DGs.
- In this lesson, let us consider the dynamical model of voltage-controlled voltage source inverters (VCVSIs) and current-controlled voltage source inverters (CCVSIs) in detail.
- Each inverter is modeled on its individual reference frame whose rotation frequency is set by its local power sharing controller.
- The inverter model includes the power sharing controller dynamics, output filter dynamics, coupling inductor dynamics and voltage and current controller dynamics.
- These last two element introduce high frequency dynamics which are apparent at peak and light load conditions and during large changes in load.

Now, as we understood that the microgrid controls scheme implies nonlinear dynamics model of the distributed generation, these are solar cells, micro turbines and wind turbines, and in this lectures, we shall consider dynamic modeling of voltage-controlled voltage source inverter, that is in abbreviation we shall use VCVSI and also this is a another inverter will be used also that is called current-controlled voltage source inverter.

So, all will be the voltage source inverter as you know that if it is required to be the current source, we require a constant source current, but there is a problem of availability of constant source current. So, we shall see that what at this among this which one will be preferred and why and how we required to model it. Each inverter is modeled on the individual reference frame whose rotational frequency is set by the local power sharing controller.

So, it may be something that you have a different microgrid and they have a, they are not pretty fixed on the voltage regulation part. Like we have an organization like power grid corporation that fix up the whole India to have a 50 hertz frequency, but you can have a small microgrid and which is having little small frequency within a limit of operation, and it said by the local power sharing controller, that is kind of our grid kind of system.

The inverter module includes power sharing controller dynamics, output filter dynamics, coupling inductor dynamics, voltage and current controller dynamics and list the 2 equivalent. These last 2 equivalent elements that is introduced high frequency dynamics which are apparent at the peak and the light load conditioning during the load change. Let us explain in why, what it is basically.

So, coupling inductor dynamics is something that it has once if it is loading, generally frequency will have a role off. Its inductance value will come down and so we require to take a precaution of kind of inductor you are designing, and voltage and the current dynamics also will change if the parameters like the inductor changes. So, in light load and full load, these characteristics will be different.

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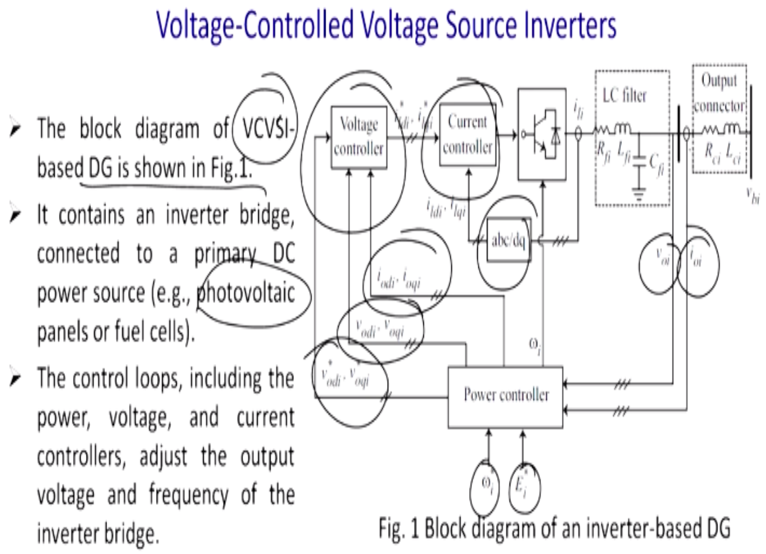

Now, this is the block diagram of voltage-controlled voltage source inverter. You will have a voltage controller. So, that will control the terminal voltage of the inverter and it will take input from this Voi as well as Ioi and ultimately it will check the frequency as well as the terminal voltage or the required voltage to be connected to the grid site and thus you got a power controller and thereafter it will feed input to this d-q frame that is Vdoi and Vqi and thereafter it will be feeding to this controller.

Then also you will be feeding the controllers of, this is the reference output voltage and output uh uh output voltage in the d-q frame. This is the actual VdVq output voltage that you are injecting in the grid of the microgrid or the point of common coupling whatever it will be, and this is the current that is you are injecting also at the PCC, and accordingly voltage controller will generate the reference for the current, that iLd start and iQd star.

They will have a current controller and this current controller will actually have an inner loop that will be a faster loop because it will walk on a switching frequency and voltage controller will be a slower loop and its bandwidth will be ten times less than this bandwidth and so you can have abc/dq transform and you will inject the power to that grid. This is the control block diagram of inverter-based DC system. Mostly in case of the solar inverter, you will see this kind of control structures.

The block diagram of the, this voltage-controlled voltage source inverter is based on DG is shown in, distributed generation, is shown in figure 1. It contains the invertor bridge connected to the primary DC source, it can be solar photovoltaic cell or it can be fuel cells. The control loops including power, voltage, and the current controller adjust output voltage and frequency of the converter. So, you will have a reference frequency and reference terminal voltage that required to be maintained in injecting it.

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Voltage-Controlled Voltage Source Inverters (cont...)

- Given the relatively high switching frequency of the inverter bridge, the switching artifacts can be safely neglected via average-value modeling.
- It should be noted that the nonlinear dynamics of each DG are formulated in its own $d-q$ (direct–quadrature) reference frame.
- Suppose that the reference frame of the i^{th} DG is rotating at the frequency of ω_i. The reference frame of one DG is considered as the common reference frame with the rotating frequency of ω_{com}.
- The angle of the i^{th} DG reference frame, with respect to the common reference frame, is denoted as δ_i and satisfies the following differential equation.

$$\dot{\delta}_i = \omega_i - \omega_{com} \quad (1)$$

Given the relatively high switching frequency of the inverter bridge, the switching artifacts can be safely neglected by that average model. So, we shall consider, it has 2 states, one is switching on state and switching off state. So, all those parameters will be having, considered in the average model. It should be noted that the nonlinear dynamics of each distributed generations are formulated in its own d-q reference frame.

So, there is a sending in a different sequence frames, PI control and tuning become easier, where this quantity looks like DC in the d-q domain. Suppose that that reference frame of this ith DC is rotating at a frequency of omega i, the reference frame of the DG is considered as a common reference with a rotating frequency of omega com. So, we can have a difference of this this thing.

So, ultimately whole systems required to be synchronized, that is the challenge, sometimes we may have a little frequency difference. The angle of ith DG reference frame with respect to the common reference frame is denoted by delta I and satisfies the following relation, that is physically you know delta i dot should be equal to delta i – delta com.

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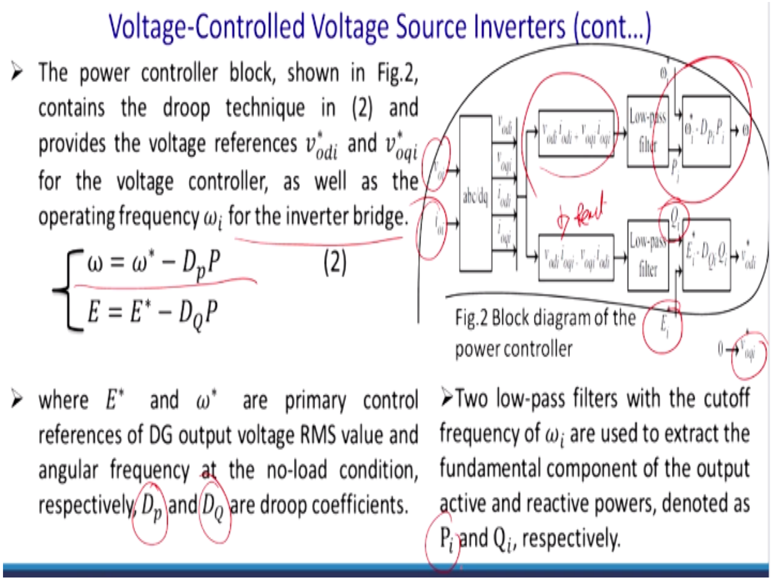

So the power control block, that is the power control block, which has been shown here also, this block essentially. So, the power controller block which we have shown there, it is been represented here. So, it has an output voltage and output current as an input. you convert to abc/dqf and thus you got these all the quantities in vDq and vD, vDq and Vd and Idq and Id; thereafter, you have a real power in d-q domain that is vDiD + vqIq and the cross product this is basically the imaginary power or reactive power.

So, vDi, vDiq – VqiD, and they are readily passed through the low-pass filters. This will actually require to control the frequency. So, you have a reference frequency, ultimately it will see that whether it is having that droop control or not, this will ensure that this frequency has been maintained by these methods, and you get Qi essentially the reactive power and the terminal voltage and from then actually you will have reference ODi. So and your VQi with respect to it required to be 0 because your power factor equal to be unity.

In that way, essentially you will operate. So, let us describe it. The power controller block has shown in the figure 2 contains the droop technique and that is the droop equation for droop technique and provides the voltage difference for Vd star Di and the Vq start di for the voltage current as well as operating frequency omega i for inverter Portage. Where E start and omega star are the primary controller reference of the distributed generator output voltage RMS value and the angular frequency at the no load conditions with respect and respectively and Dp and Dq are the droop coefficients.

The low-pass filters with the cutoff omega i are used to extract the fundamental component of the output of the active reactive powers, denotes the Pi and Qi respectively. It may be so that the system has a harmonic, so we will have a harmonic power. So, once you pass through the low-pass filters, this harmonic power gets eliminated, you have average DC power.

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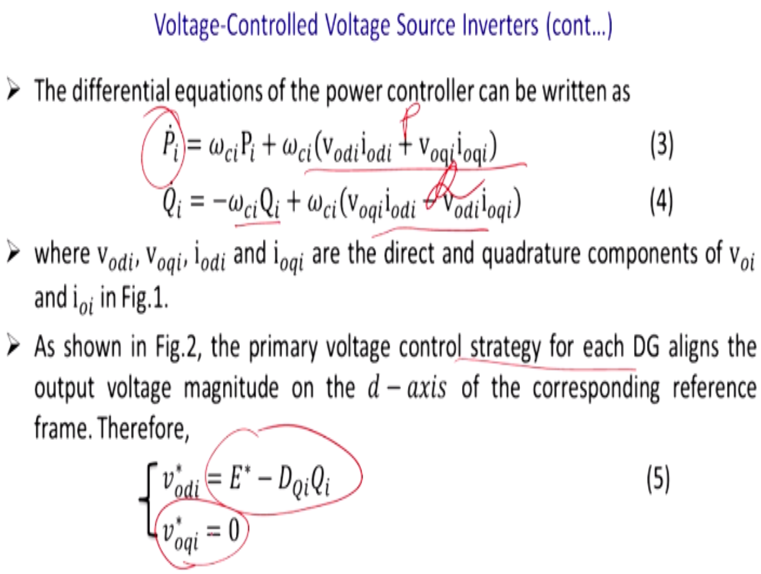

So, if you differentiate this equation Pi, this power (( )) (11:49) power equations, you get omega ciPi because it is and + omega ci x the real power. Similarly, if you differentiate the reactive power, then you get –omega ciQi + omega ci of this R. This one is again P and this one is again Q. So where Vdi and Vqi, odi and oqi are the direct and quadrature axis of the Voi and ioi.

And this figure 2 we have seen that the primary voltage control strategy for the each distributed generator aligns the output voltage magnitude to the d-axis to the corresponding reference, so that you have aligned your a-axis with the d-axis and you have unity power factor operation and thus this is the droop, odi should be E – Dqi x Qi and this should be equal to 0.

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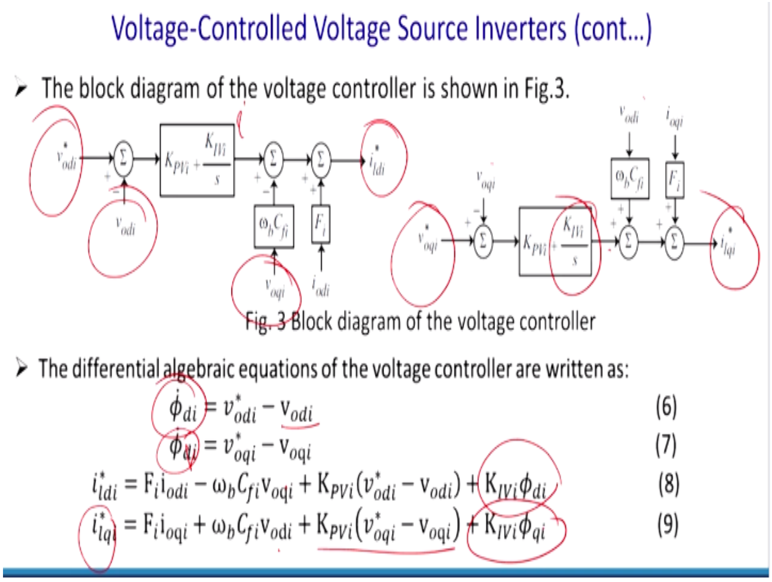

So, voltage-controlled block diagram of the inverter. Now essentially what you have seen in the first figure, this low go back or you can turn your lectures, ultimately this is this, we are going to discuss this. So, let us see how it will work. So, you got the reference odi from this previous equations and you have actual Vodi. So, you will subtract it, then you will put it to the PI controller and this component should be DC in the d-q domain.

Thus tuning of this parameters in the DC here easier and for this reason we prefer to walk into the ABC, instead of ABC we use walk for the d-q frame. So, then you got essentially the Vqi and output of this thing will be the current and you will sum up the current and you will sum up the current for the filters that is oqi based frequency to Cfi and similarly odi into fi, ultimately this will give you the direct access reference current. Same way, ideally this value should be 0.

So this value will subtract, you will you will feed, you will compare with this Pi and you have Odi + omega Cfi, it has to be add up, this part of the current, and thereafter you will have this frequency into a and ultimately you get the iq reference. Now Cfi is which will tell, let us see this block diagram, then only you will understand. You know Cfi is this filter. So, this is the overall block diagram to generate the reference id start and the ld start, iq start and id start.

The differential algebraic equations or the voltage controller can be rewritten as you know this is a flux reference, differentiation of the flux gives us the voltage. So, in for the ith generator in d-axis, flux will be equal to Vd start odi – vdi. Similarly we can rewrite this one as Vqodi and by substituting this results here, so id star, we can rewrite that is Fiodi – this one

+ Kp this thing + phi, essentially it is integrating you know these voltages, thus if this value becomes flux since there is an integration involved.

So your feeding voltage essentially here you are getting a flux. So, this Kivi x di essentially is that current. Similarly, q-axis current will be same, instead of the d, it will have a q. So here instead of the q here, it will have a d, thereafter this proportional term and thereafter this integral term, that is Kipv x phi qi.

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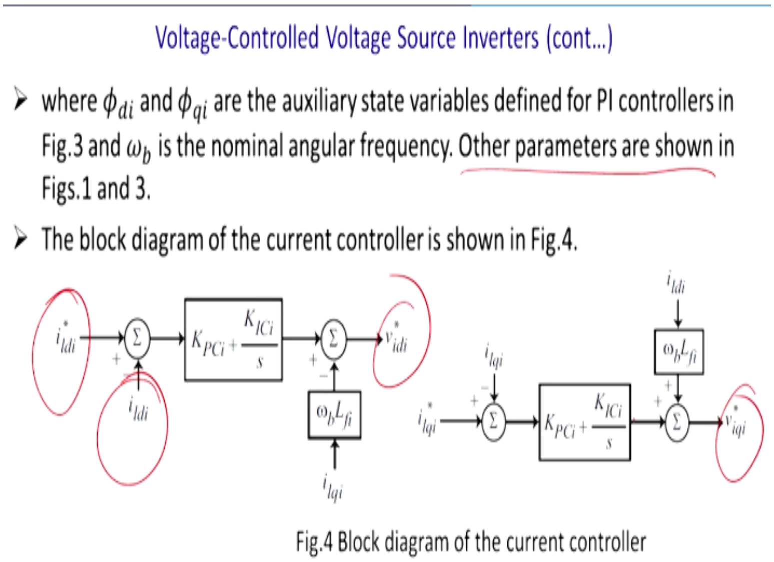

So, where phi di and the phi qi are the auxiliary state variables of the PI controller in the controller in figure 3 and omega b is the nominal angular frequency and the parameters are shown in the figure 1 and 3. And now, let us see the current control block. So, you got reference for the iq, id axis and you have got a reference from the, this is actually you will compare it, then you may put it to this actually the PI controller.

Then you compare with the current through the inductor and multiply with the omega b x Lfi and ultimately this essentially gives you the voltage. So, you got a voltage. So, this voltage difference is really vd start. Similarly, iq start you got and ultimately you can feed it to this current controller and thus you get the vq star.

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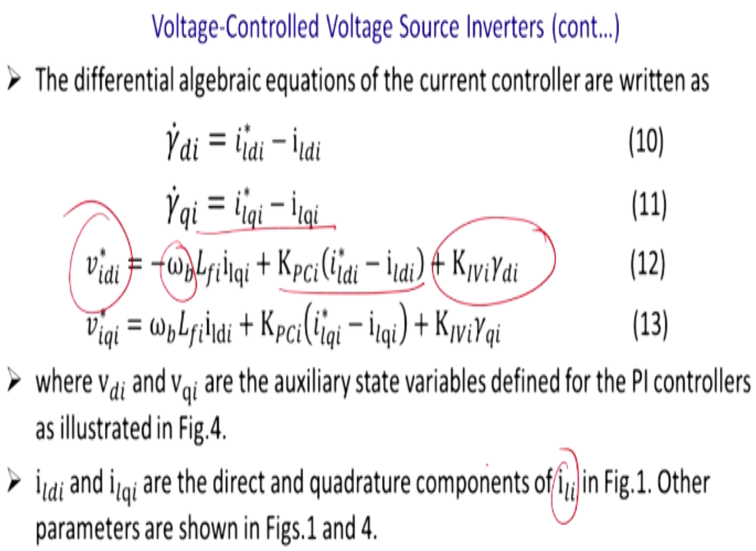

So, general algebraic equations of the current controller are written as lambda di = ildi x ildi. So, if you differentiate it, similarly you got essentially this value of q-axis and if you substitute it, that is that d-axis inverter voltage, there is lambda d like that is a omega bLfi x Lqui + this current controllers, PI controller term + this one since it is integrating the current.

So that will be a charge, so into lambda x di and where vd and vq are the auxiliary state variable of the PI controller of the state variable for ilqui and ilqdi, the direct and the quadrature axis component of that load current li and other parameters are shown in this figure.

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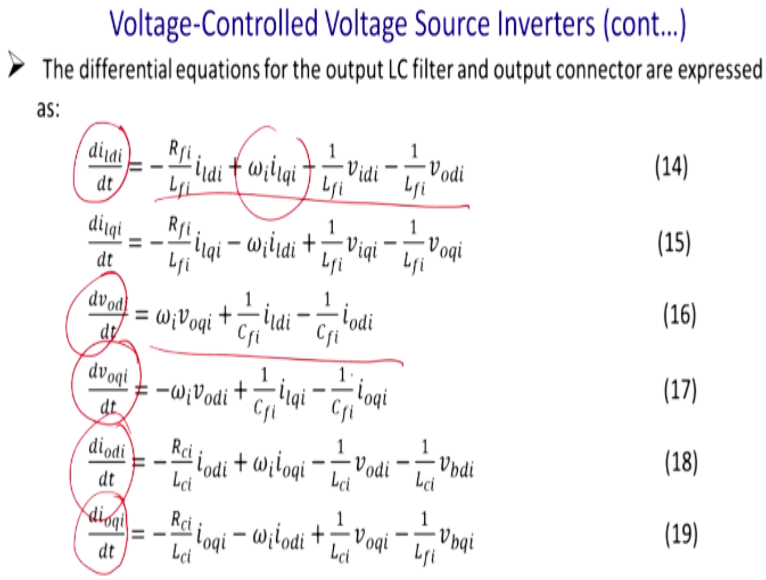

So, based on that, we have a whole set of equations. So, these are the state variable and ultimately, we require to write the CCVSI model. So, it is the di/dt of dl of load current in d-axis, so you got this parameter. You can write in the observation, that is Rf/Lf because you got a resistance x ldi with omega, there will be q term iq and thereafter -1/Lf x vdi – 1/Li x void. So, you can write it all those parameters.

So, this is vi, this is void and similarly, in case of the iq, just there will be a change in the expression, there will be these 2 term will be minus and instead of this qi, it will be di and other terms will be almost the same. Thereafter, you write it for dv/dt also, that is essentially the current and you get these equations, that is omega qi, thereafter, that is for the d-axis, similarly vo this for the q-axis, thereafter io that is for the d-axis, thereafter io for the q-axis.

So, you have 6 equations. So, it will be you will have 6 uh 6 by 6 matrix as your state space for analyzing your voltage source voltage-controlled inverter. Thus, you can write in the form of rest of the equation.

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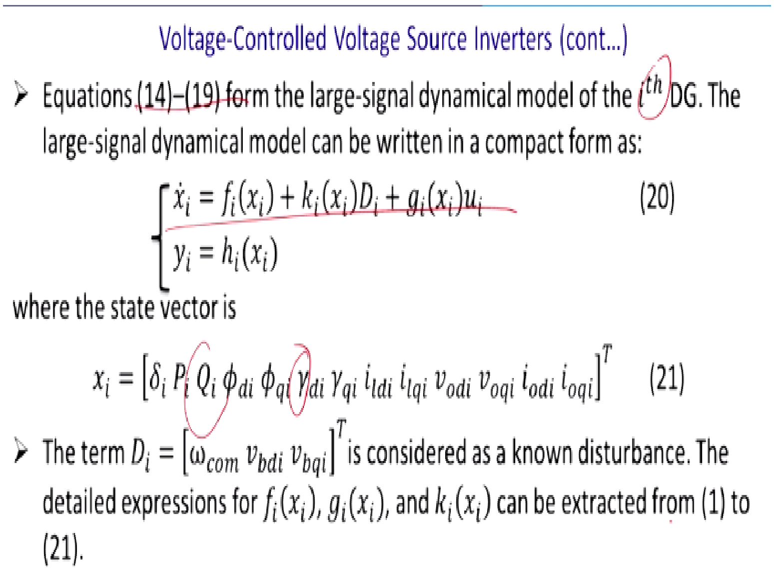

So, this 14 to 19 form large-signal dynamical model and it is an average model, we have told it, it is ith DG. The large-signal dynamic model can be retained in a compact form definitely, it is physically the fxi + kiDi + gi and of course y = hixx. Where state vectors are phi I Pi Qi Di and all those things, lambda, This is so, you have a huge setups. We cannot use charge, integration of the current definitely gives you the charge. We use lambda because of the fact that you know we already use q as it active power.

So, please keep in mind that we have used lambda for the charge and phi for the integration of the voltage, this is same for the flux, but we require to change, we cannot use q because we are using q for reactive power. So, the term Di is omega com vbdiqui is considered as a disturbance and the detail expressions for fi gi and ki can be extracted from the 1 to 21, whole equation required to study, and the students are required to revisit the transfer functions, conversion from the status to transfer function, then only they can realize the transfer functions of the system.

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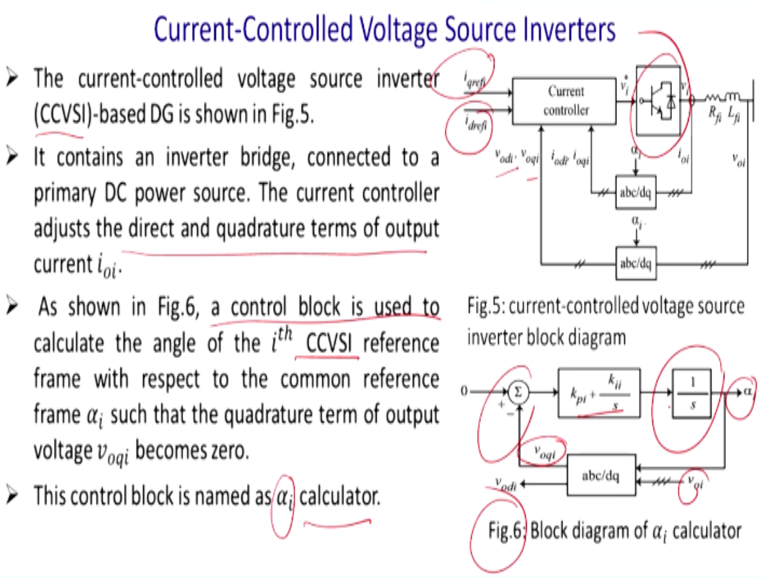

So, the current-controlled voltage source inverter, we now come to another interesting topic. Previously we had a voltage-controlled voltage source inverter. Now, we will come across current-controlled voltage source inverter. Of course, it will be in a it is called it will be controlled in the d-q frame. It contains an inverter which this one connected to our primary DC source, it can be a solar cell or the fuel cell.

The current controller adjusts a direct and the quadrature term of the output current ioi. As shown in the figure 6, a control block is used to calculate the angle of the ith cc CCVSI reference frame with respect to the common reference frame alpha i such that the quadrature term of the output voltage voqi become 0. This control block diagram is named as alpha I calculator. So, we shall see that how does it work.

Ultimately you have vdq and vq reference frame, you will sense the voltage and thereafter you convert to this ABC to dq frame and it is your output voltage and thus you transform into the your vd and vq. Thereafter, you have inner current control loop, so you trans, you may set this ioi, then it convert to the d-q frame, you have iq and dq reference and you have a vi. So, that reference is a modulating signal for this controller and the block is named as a now the second block, it is essentially your alpha i calculated.

So, alpha i essentially is something like pll. So, you require that theta. How does it work? You know you have voi and you have you will convert to the vdq to alpha beta to add that ABC frame and you have a vqi and once you have aligned your A phase with the D phase, then q-axis should be equal to 0 and thus it is compared with the 0 vqi, then you fed to this PI controller and definitely, thereafter, it becomes omega, this is a proportionality term.

If you integrate omega, essentially it will become alpha and that alpha or theta whatever will be the desired theta and this is the PLL. It is being generated in this way for the current-controlled voltage source inverter.

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Current-Controlled Voltage Source Inverters (cont...)

- The block diagram of the current controller is shown in Fig.7.

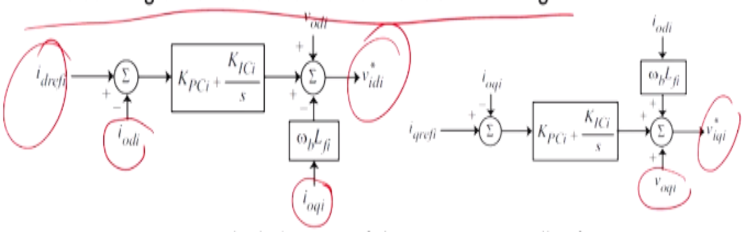

Fig.7: Block diagram of the current controller for a CCVSI

- The differential algebraic equations of the current controller are written as:

$$\dot{\gamma}_{di} = i^*_{drefi} - i_{odi} \quad (22)$$

$$\dot{\gamma}_{qi} = i^*_{qrefi} - i_{oqi} \quad (23)$$

Now, let us discuss the block diagram of the current-controlled voltage source of the figure 7. So, you have id reference and you have generated the fields referred to this block that you have this one. So, you fit to the PI controller and thereafter you actually whatever the reference voltage you get, you then multiply with this omega blfi and subtract vodl, ultimately you get the error.

So, that will be your reference idi, the reference in reference modulation index into or sub that related to that parameter and similarly, you have iq, iqrefi and iqi, you subtract then kp kpci + kiciys, then multiply with omega blfi, so minus obqi and ultimately you get viqi. The differential algebraic equations of the current controller is written as, so this is also the charge.

So, that is lambda idt = idref - iq - iodi. Similarly, here for q-axis, it will be iqrefdi – iqy. Mind it there is a since there is a dimensional problem, so it is an orientation, so you should not come confuse with the vectors, current is not at all a vector and ultimately if you have integrated, so, in a new axis it is just a d-q, just an orientation, is not a vector.

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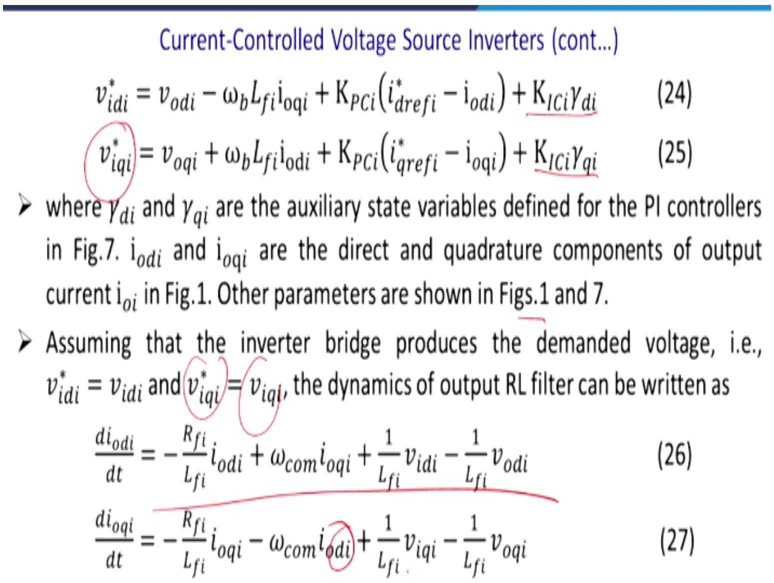

So, vidi = void – omega b Lfi oqui + the PI controllers and this value. Similarly, for the q-axis, you got voqi + omega Lfi a cross product, so it will be d + Kpci pqref – iqref + this Kici lambda qi, where lambda di and lambda qi are the auxiliary state variables for the PI controllers for the current control loop and this figure 7, odi and oqui are the direct and the quadrature axis component of the output current ioi in the figure and other parameters are shown in figure 1 and 7.

So, now let s then again we have to write the statements modeling of it. Assume that inverter bridge produces that demanded voltage, that mean that vdi = vd star = idi and I viqi start = this referred parameter matches with that and dynamic output voltage then it can be written as di/dt that will be these parameters that is Rfi/Lf x odi, this is a cross term, omega m x iqi, thereafter, 1/Lfivqi and – 1/Lfi void. Similarly, for q-axis, so this term will be your d and other terms will be q as it is. So, this is followed, but there will be a sign change from the q-axis.

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Current-Controlled Voltage Source Inverters (cont...)

- Equations (22)–(27) form the large-signal dynamical model of the i^{th} CCVSI.
- The large-signal dynamical model can be written in a compact form as:

$$\begin{cases} \dot{x}_{CCi} = f_{CCi}(x_{CCi}) + k_{CCi}(x_{CCi})D_{CCi} + g_{CCi}(x_{CCi})u_{CCi} \\ y_{CCi} = h_{CCi}(x_{CCi}) + d_{CCi}u_{CCi} \end{cases} \quad (28)$$

Where the state vector is

$$x_{CCi} = [\gamma_{di}\ \gamma_{qi}\ i_{odi}\ i_{oqi}]^T \quad (29)$$

- The term $D_{CCi} = [\omega_{com}\ v_{odi}\ ]^T$ is considered as a known disturbance.
- The detailed expressions for $f_{CCi}(x_{CCi})$, $g_{CCi}(x_{CCi})$, and $k_{CCi}(x_{CCi})$ can be extracted from (28) to (29).

So, the equation 22-27 is a large-signal dynamic model for the kth current-controlled voltage source inverter and so you can rewrite in a short version that is in a CCVSI modeling xcci = fcci + kcci Dcci and these are your state variable and this term is considered as a disturbance. These are your vdcom and void and then you can have robustness studies whatever studies you want, you to do that in a, this is a control dormant and detailed expression of fi, gci, and kci can be extracted from the 2 equations by writing this long form.

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Control Objectives of AC Microgrid

- The proper control of microgrid is a prerequisite for stable and economically efficient operation.
- The principal roles of the microgrid control structure are as follows
  - Voltage and frequency regulation for both operating modes
  - Proper load sharing and DG coordination
  - Microgrid resynchronization with the main grid
  - Power flow control between the microgrid and the main grid
  - Optimizing the microgrid operating cost
  - Proper handling of transients and restoration of desired conditions when switching between modes.

Now, let us come to the point of control objective or the microgrid. The proper microgrid is a, proper control of the microgrid is a prerequisite for the stable and economic efficient operation. So, whatever statements you have you got through our transfer function and you should have a stability steady and that is instead of mathematics if you put in words, we should say those things here now. The principal roles of the microgrid control structures are as follows.

Voltage and the frequency regulation for both the operation modes, it is possible in voltage and current voltage and frequency both to be controlled. Proper load sharing and coordination between different DG because one can be a source, otherwise another will be a load, so this kind of problem will be there. Microgrid resynchronization with the main grid if required you are trying to dispatch power to the main grid, that is also possible.

Power flow between the microgrid and the main grid and vice versa. Optimizing the microgrid operating costs. Proper handling of transient and restoration of the desired condition when switching between the different modes. So, these are the some criteria we wanted to get into it by this modeling.

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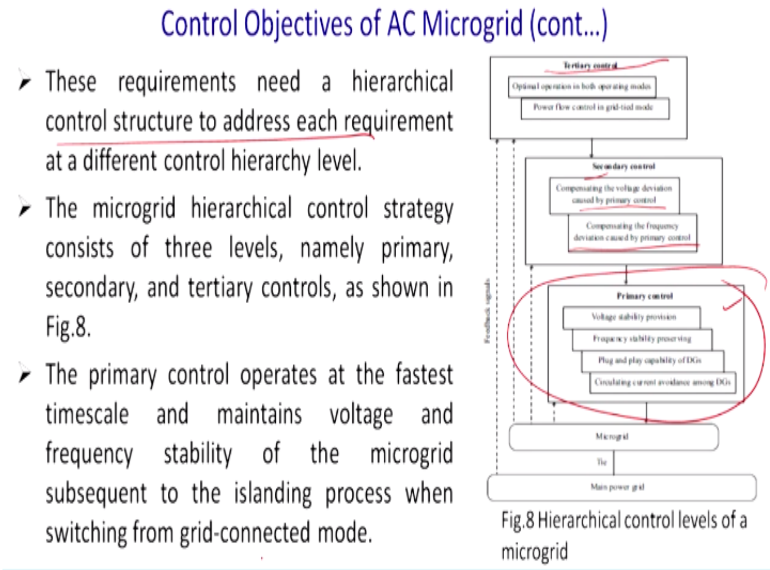

So, this requirement needs a hierarchical control structure and a different control hierarchy. So, this is a, so you will have a tertiary control overhead, optimal operation in both operating mode, then power flow control in that grid tried mode. Then you can have a second layer operation that is called a secondary question, compensating the voltage deviation caused by the primary control, compensating the frequency deviation caused by the primary control. Then primary control is the, these are the primary controls.

So voltage stability provisions, frequency stability provision, plug and play capability of the DG, so switch, switch it on and switch it off as you wish, and circulating current avoid among the DGs; these are the primary control. So, accordingly we have a different task has been identified for the different people. So, this is a primary control that will be done with the inverter level.

This is the secondary control, this is the task of all those things, and it is a tertiary control, mostly where disconnected to a detect mode, generally the grid operation will prevail and ultimately that will be their control. The microgrid hierarchical control strategy consists of the 3 levels, namely primary, secondary and tertiary. The primary control operates at the fastest time scale. So, it will operate quite fast and maintains the voltage and the frequency stability of the microgrid subsequent to the islanding operation when switching from the grid to the connected mode.

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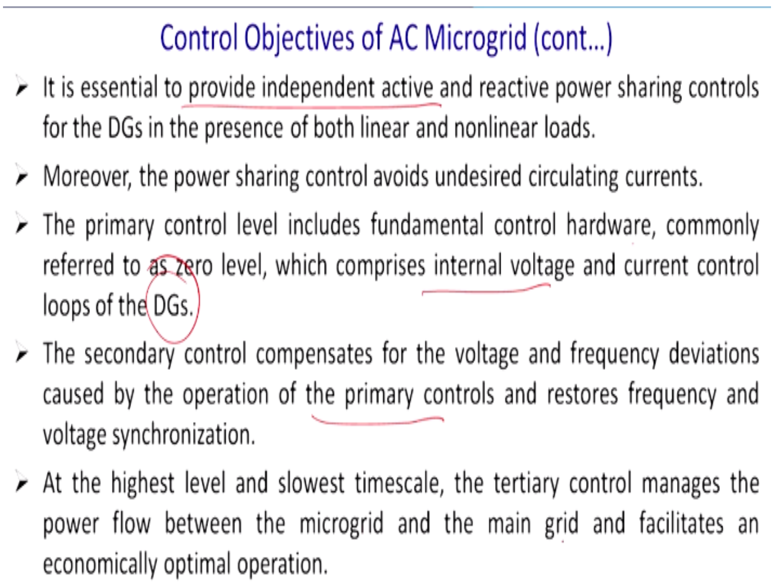

Now, what are the control objectives? It is essential to provide independent and active, independent active and reactive power sharing control for the DGs in the presence of both linear and the nonlinear load. This is something we require to handle. Moreover, power sharing control avoids undesired circulating current, this is the primary control we have seen. Primary control level includes fundamental control hardware control of hardware, commonly referred to as a zero level, which comprises the term internal voltage, current control loops and distributed generators.

Secondary control mainly compensates the voltage and the frequency deviation caused by the operations of the primary control and restores the frequency and voltage synchronization. The highest level, that is the slowest timescale, the tertiary control manages the power flow between the microgrid and the main grid and facilitates an economical operation in this case. So, thank you. Thank you for your cooperation. We should continue with the microgrid modeling in your next classes.