DC Microgrid and Control System
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Lecture - 29
DC Microgrid Dynamics and Modeling

Welcome to our lecture on the DC microgrid and the Control System. We shall today discuss in detail that modeling of the DC microgrid, that is the microgrid dynamics and its modeling.

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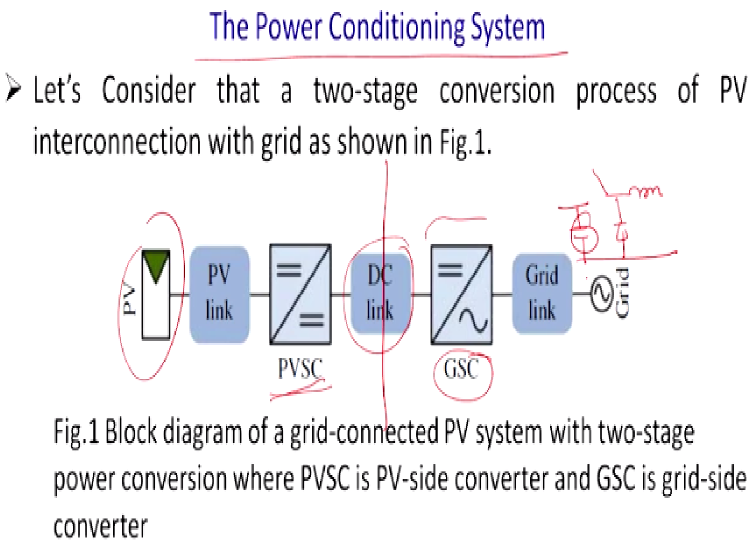

The Power Conditioning System

- Let's Consider that a two-stage conversion process of PV interconnection with grid as shown in Fig.1.

Fig.1 Block diagram of a grid-connected PV system with two-stage power conversion where PVSC is PV-side converter and GSC is grid-side converter

So, so let us consider that first power conditioning system. So what you have? You have a one PV and thus you got up a PV link that is that will transmit the power and ultimately, you will track the maximum power point and all those things. For this reason, you got a DC to DC converter. One DC to DC converter will try to track the MPPT, another DC to DC track uh converter will give you the desired voltage level and thus you come to the DC link and from this DC link, this is the entry point and there it may require to have a preprocessing to get the desired DC bus voltage.

Thus you have this grid connected inverter and you have a grid link, essentially it is a PWM inverter, and for this reason, it will inject high frequency harmonics and to bring down that harmonics level to the desirable level, you have the filter essentially that is your grid link. So for this reason, we can say that let us consider the two-stage conversion of the PV interconnections with the grid as shown in the figure.

So, first part is your DC part and if it is a DC microgrid, so and this is essentially you have to be this is essentially the follow with the active power filter and all those things or active rectifier. So, this part is essentially a DC to AC conversion and thus what you can say that this is a block diagram of the grid connected PV system with two-stage power conversion, this is one stage and another stage, where PVSC, so this one, it is the PV side converter, is the PV side converter and GSC essentially it is DC to AC is a grid side converter. So, both the converter you required to place it.

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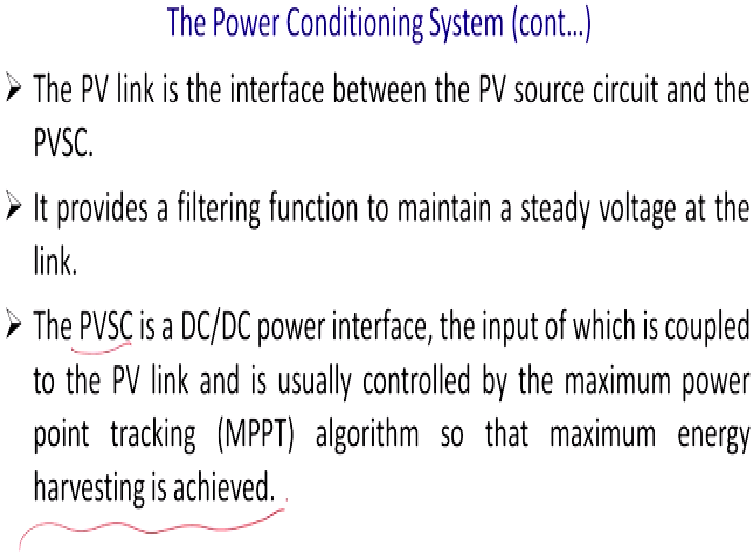

The Power Conditioning System (cont…)

- The PV link is the interface between the PV source circuit and the PVSC.
- It provides a filtering function to maintain a steady voltage at the link.
- The PVSC is a DC/DC power interface, the input of which is coupled to the PV link and is usually controlled by the maximum power point tracking (MPPT) algorithm so that maximum energy harvesting is achieved.

The PV link is interfaced between the PV source circ uh PV source circuit and the sv and the PVSC, that is PV side converter, and that require a link essentially and that task of this link two mainly; if it is a pure DC doesn't matter, but since it has a switching, so, we required to, if it s a buck converter, so what happened you were temporarily making a connection off and you are maybe bucking.

So, then what will happen? MPPT point will be shifting maybe and thus you required to sink some amount of the current in this capacitor and you have a ripple. So, this PV link will be this combination of the capacitor inductor and that gives you a ripple free voltage at that at the at the input to the PVSC. So, for this reason what we can say, it provides filtering function to maintain steady voltage at the link, and what happen, and sometimes you are shorting if you use a boost converter, so that also you required to consider,

So, for this reason, you required to have that filter. So, the current value does not fluctuate at a very high extent. The PVSC is a DC to DC uh power interface, the input of which is coupled to the PV link and is usually controlled by the maximum power point tracking algorithm, so that the maximum energy is energy harvesting is achieved. So, that we can take what solar generate at max.

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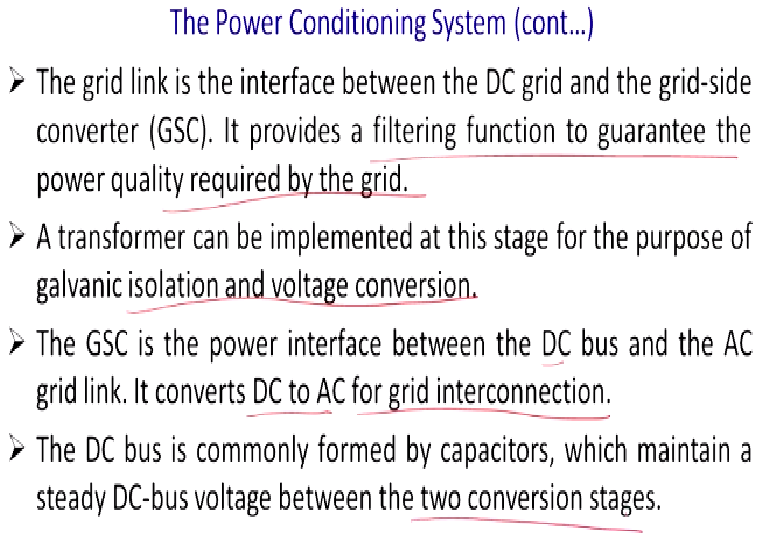

The Power Conditioning System (cont...)

- The grid link is the interface between the DC grid and the grid-side converter (GSC). It provides a filtering function to guarantee the power quality required by the grid.
- A transformer can be implemented at this stage for the purpose of galvanic isolation and voltage conversion.
- The GSC is the power interface between the DC bus and the AC grid link. It converts DC to AC for grid interconnection.
- The DC bus is commonly formed by capacitors, which maintain a steady DC-bus voltage between the two conversion stages.

Thereafter, let us come to the power conditioning unit. So, your MPPT voltage depending on the string length and all those things, you were aiming, you were generating some kind of DC voltage level, but your DC bus has been connected to the may be the 48 volt, and for this reason, you require another DC to DC converter into this and that will be mentioned as your PVSC, and similarly, if you are injecting power to that grid, then you require AC to DC, DC to AC conversion and that will be named as grid-side converter.

For this reason, what we are saying the grid link in the interface between the DC grid and the grid-side converter, it provides the filtering function to generate to guarantee the power quality as required by the grid court. So, whatever the great court, it has been specified by the particular state of the law, so you have to follow that. The transformer can be implemented at this stage for the purpose of the galvanic isolations and the voltage conversion because after that, it is a DC to AC stage after inverter.

If you wish to connect a high volt, you generally hook up to the high voltage, and for this reason that depends on which point you do the power, which point means which voltage level you evacuate the power because you know if you are injecting a huge amount of the power, ultimately you cannot evacuate in a distribution network, you may have to evacuate a uh in a generation or in a transmission network.

So, you may if you have a putting a power plant and you are then maybe your generation may be the 5 megawatt, so, you cannot add that power in a distribution level, you have to add that power into this transmission level, may be the 33 kV (( )) (07:32) bus. So for this reason, you require a step up the transformer and thus the transformer provides galvanic isolations and that is also the power of the great court.

Like for the example that European Union mandatory requirement is the transformer and but there are some countries like China, all doesn't require the galvanic isolation in a distribution level. The GSC is the power interface between the DC bus and a the AC grid link, it converts DC to AC for the grid interconnections, that is the whole purpose of it. The DC bus is commonly formed by capacitors, which maintains steady DC bus voltage between the two conversion stages.

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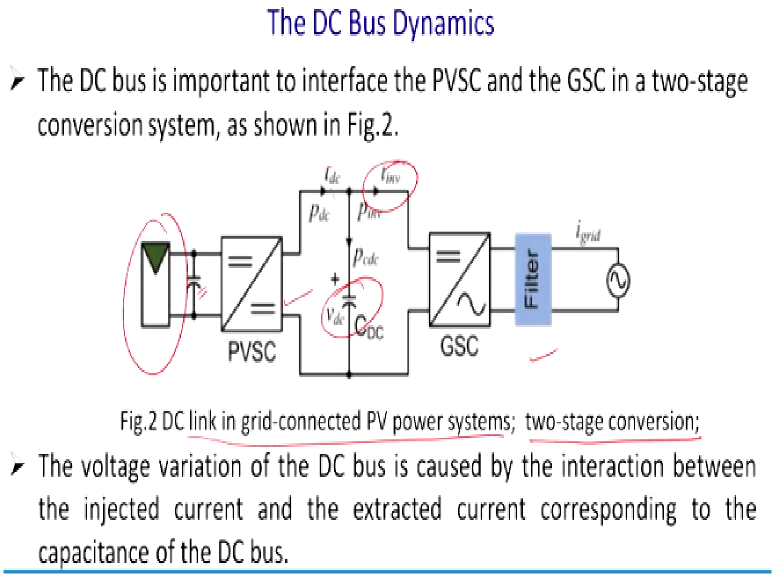

The DC Bus Dynamics

- The DC bus is important to interface the PVSC and the GSC in a two-stage conversion system, as shown in Fig.2.

Fig.2 DC link in grid-connected PV power systems; two-stage conversion;

- The voltage variation of the DC bus is caused by the interaction between the injected current and the extracted current corresponding to the capacitance of the DC bus.

Now, this is the figure 2 which shows the DC link grid connected PV power system for that two-stage conversion. The DC bus is important to interface the PV side converter and the grid side converter in a two-stage conversion system. First you got a solar panel, thereafter you got a capacitor I told you, you know there can we are momentarily blocking of voltage or current and depending on the topologies of this converter, DC to DC converter, for this reason, you require a input capacitor.

Thereafter same way, there might be an instantaneous mismatch between this to power generation and in power supply, that has to be fed form or supplied into the storage element like capacitor. And apart from that, you know till this point it is DC, thereafter, it will be the inverter current, and for this reason, we require to model this capacitor rightly, so that it can sink that amount of current.

So, what we can say here that the voltage variation of the DC bus is caused by the interaction between the injected current and the extracted current corresponding to the capacitors of the DC bus. So, the current here it is entering and currently here it is leaving. If more current is entertaining and less current is leaving depending on the load, but it is not a problem because since you can consider grid as an infinite load.

So, then voltage may sink and vice versa if you are trying to supply the more load, then you the capacitor voltage will sink, and thus you have to have a balance existed because if you are putting charge into the capacitor, voltage will soil, and if you are taking out charge from the capacitor, voltage will sink. Thus you are required to have balance between the idc and the inv.

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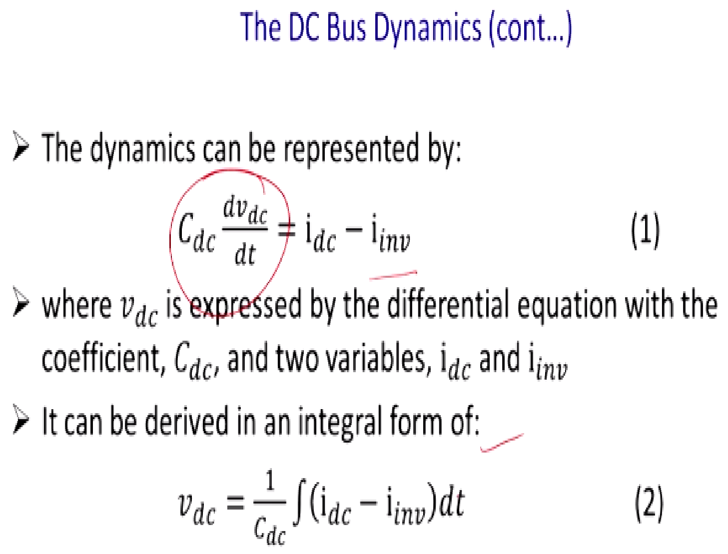

The DC Bus Dynamics (cont...)

- The dynamics can be represented by:

$$C_{dc}\frac{dv_{dc}}{dt} = \mathrm{i}_{dc} - \mathrm{i}_{inv} \qquad (1)$$

- where v_{dc} is expressed by the differential equation with the coefficient, C_{dc}, and two variables, i_{dc} and i_{inv}
- It can be derived in an integral form of:

$$v_{dc} = \frac{1}{C_{dc}}\int(\mathrm{i}_{dc} - \mathrm{i}_{inv})dt \qquad (2)$$

So, what we can write you know, so dynamics can be represented by Cdv/dt = idc is the current that has been generated by the DC to DC converter in the PV side and ultimately you have fed to a grid-side inverter that value is the inv. So, that ripple current should be called to dv/dt. More is the difference, more will be the ripple current into the capacitor. Ultimately, Cdv/dt will compensate that amount of defer amount of the deficits.

Where DC expressed by, where the DC expressed by the differential equation within the coefficient and Cdc are the two variables idc and inv and thus from there, we can integrate up and the Vdc will be 1/Cdc integration of dc and inv dt and want that value of the Vdc almost maintain constant, so that ripple in that capacitor is less.

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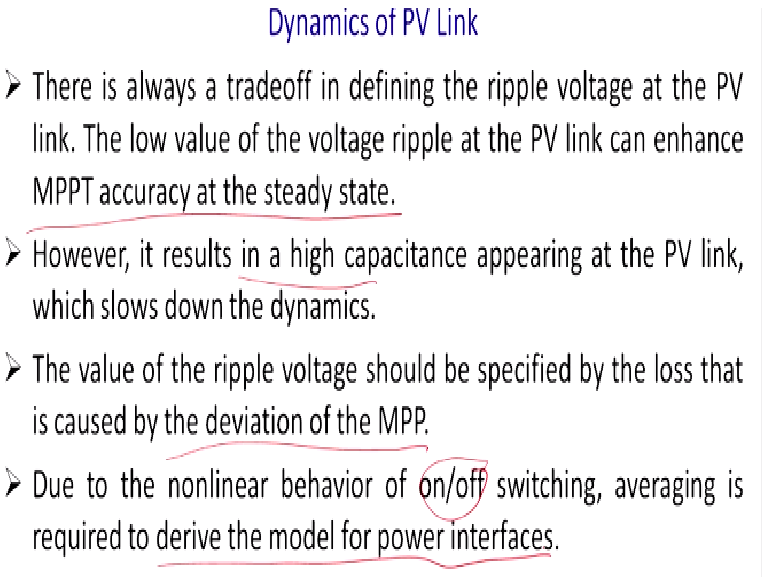

Dynamics of PV Link

- There is always a tradeoff in defining the ripple voltage at the PV link. The low value of the voltage ripple at the PV link can enhance MPPT accuracy at the steady state.
- However, it results in a high capacitance appearing at the PV link, which slows down the dynamics.
- The value of the ripple voltage should be specified by the loss that is caused by the deviation of the MPP.
- Due to the nonlinear behavior of on/off switching, averaging is required to derive the model for power interfaces.

So there is always tradeoff in defining the ripple at the PV link. Lower the value of the ripple at the PV link can enhance the MPPT accuracy and the steady state operation. However, you required to put definitely you know, you are required to put a higher value of the capacitor; however, it results a results in a high capacitance appearing at the PV link, which slows down the dynamics, that mean if you want to track or you change the irradiation condition, you require to change one state to another state.

This change will be slower if the value of the capacitor is the is high. So, value of the ripple voltage should be specified by the by the loss that caused by the deviations from the MPP, so that has to be mentioned in your operation. Moreover, due to the nonlinear behavior of the what you are essentially doing is a switching, thus it is uh on/off control, and for this reason it is it has got a nonlinear dynamics, maybe our on/off switching averaging is required to derive the model for the power interfaces, that is something we require to keep in mind.

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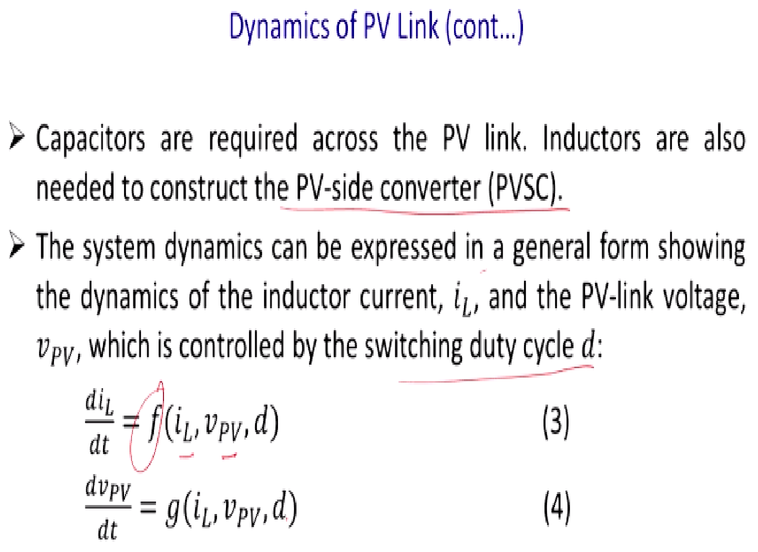

Dynamics of PV Link (cont...)

- Capacitors are required across the PV link. Inductors are also needed to construct the PV-side converter (PVSC).
- The system dynamics can be expressed in a general form showing the dynamics of the inductor current, i_L, and the PV-link voltage, v_{PV}, which is controlled by the switching duty cycle d:

$$\frac{di_L}{dt} = f(i_L, v_{PV}, d) \quad (3)$$

$$\frac{dv_{PV}}{dt} = g(i_L, v_{PV}, d) \quad (4)$$

Capacitors are required across the PV link, inductors are also needed to construct the PV side of the converter. We require capacitor so that you know what happened, you either stop the voltage that on the kind of topology you are using. If you are using a buck converter, essentially for the interval when switch is off, you are stopping the current, and also in case of the boost topology, you are making the source short through an inductor.

So, either of the case is to hold that value of the voltage and current, we required to put a small capacitor. For this reason, we say that capacitor is required across the PV link, inductor also needed to construct that PV side converter. Why we require an inductor in the PV side converter because you need to smoothen the current profile and you got almost steady state value of the current and its control also become easier.

We shall see how that control has been done and you will find that value of the inductor is essentially try to make the current continuous and thus you have a you can operate this converter into the continuous conduction mode, and once you are operating in a continuous conduction mode, you have better control over on your topology. The system dynamics can be expressed in general form showing the dynamics of the inductor current iL and the PV link voltage that is vPV, which is controlled by the switching duty cycle d.

So, iL ideal di/dt is a function of iL PV and the duty cycle, and similarly, the vPV will be again the function of this same parameter iL PV and the duty cycle.

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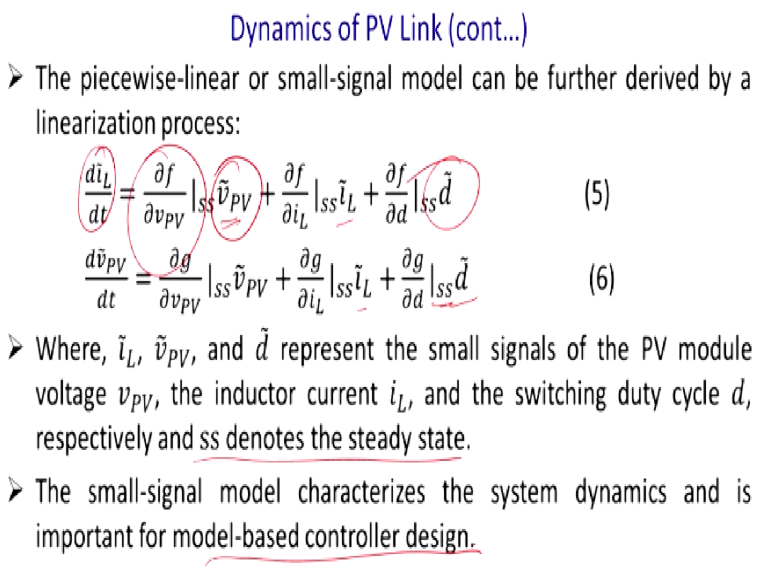

Dynamics of PV Link (cont...)

- The piecewise-linear or small-signal model can be further derived by a linearization process:

$$\frac{d\tilde{i}_L}{dt} = \frac{\partial f}{\partial v_{PV}}|_{ss}\tilde{v}_{PV} + \frac{\partial f}{\partial i_L}|_{ss}\tilde{i}_L + \frac{\partial f}{\partial d}|_{ss}\tilde{d} \qquad (5)$$

$$\frac{d\tilde{v}_{PV}}{dt} = \frac{\partial g}{\partial v_{PV}}|_{ss}\tilde{v}_{PV} + \frac{\partial g}{\partial i_L}|_{ss}\tilde{i}_L + \frac{\partial g}{\partial d}|_{ss}\tilde{d} \qquad (6)$$

- Where, $\tilde{i}_L$, $\tilde{v}_{PV}$, and $\tilde{d}$ represent the small signals of the PV module voltage v_{PV}, the inductor current i_L, and the switching duty cycle d, respectively and ss denotes the steady state.
- The small-signal model characterizes the system dynamics and is important for model-based controller design.

Thus, we have to take the piecewise-linear model and thus we will give a normalized value, thereafter a perturbation. So, what we can find, so del iL = partial derivation of the of this functions with respect to do dot dv and thus as you can have that is this delta terms is the perturbation, part of term, that is small disturbance. So, if you have and that is that inductor current will change for the perturbation of the PV voltage as well as the perturbation of the PV current as well as the perturbation of the duty cycle.

Similarly, the PV voltage will change for the perturbation of the PV voltage as well as the current through due to the inductor as well as the duty cycle. So, where we say that this delta iL vPV and d represents the perturb quantity or the represents a small signals of the PV modules, voltage, and voltage PV and the inductor current iL and the switching duty cycle d respectively and ss essentially it is a it denotes the steady state value, that when you are not accounting any transient because once you refer to the transfer functions, transfer function always refer to the steady statement, ss denotes the steady state.

The small-signal model characterizes the system dynamics and is important for the model-based controller design.

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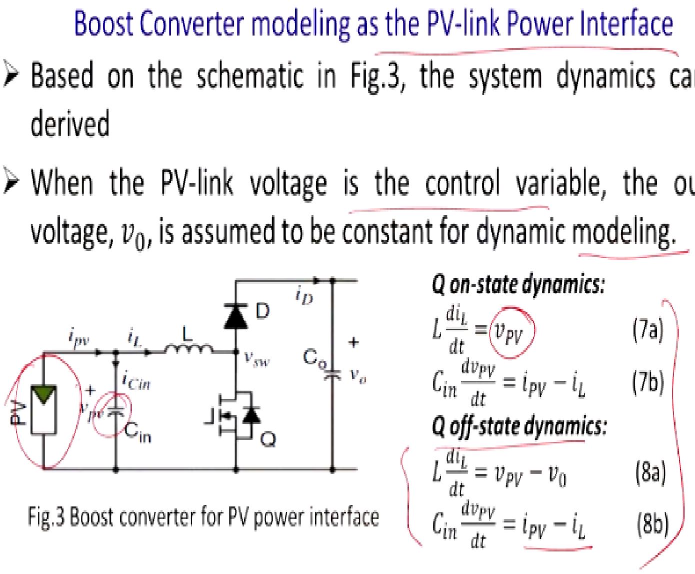

Boost Converter modeling as the PV-link Power Interface

- Based on the schematic in Fig.3, the system dynamics can be derived
- When the PV-link voltage is the control variable, the output voltage, v_0, is assumed to be constant for dynamic modeling.

Q on-state dynamics:

$$L\frac{di_L}{dt} = v_{PV} \qquad (7a)$$

$$C_{in}\frac{dv_{PV}}{dt} = i_{PV} - i_L \qquad (7b)$$

Q off-state dynamics:

$$L\frac{di_L}{dt} = v_{PV} - v_0 \qquad (8a)$$

$$C_{in}\frac{dv_{PV}}{dt} = i_{PV} - i_L \qquad (8b)$$

Fig.3 Boost converter for PV power interface

Now, let us take that topology to be the boost, PVSC to be the boost topology. Now, what will happen, the boost converter and modeling of the DC link power interface and based on the schematics of the figure 3, the system dynamics can be derived as follows. When the prevailing voltage is that control variable, the output voltage v0 is assumed to be constant for dynamic modeling. So, it is a PV. So, you got iPV, essentially you got a capacitor, thereafter you got an inductor.

So, what happened, if you don't give the capacitor, ultimately what happens, if you short it, then there will be a huge drip in MPPT point. So, voltage will supposed to collapse at this point and what will happen, high current will flow and thus MPPT point will change, and this capacitor will ensure that this MPPT point almost as close will switch on/off takes place. So, based on the schematic in the figure 3, the system dynamic can be derived when the prevailing voltage is the control variable.

The output voltage v0 is assumed to be the constant for dynamic modeling and Q on-state dynamics that is LdqL/dt = PV; Cin PV/dt = PV-iL. So Q off-state dynamic equal to LdiL/dt = PV-v0, from there, you can get Cin dv/dt – PV – iL. So, here is the equation. So, you have a couple of equations corresponding the on state of this converter and this is a couple of equations, 8 a and b are the off-state of the converter.

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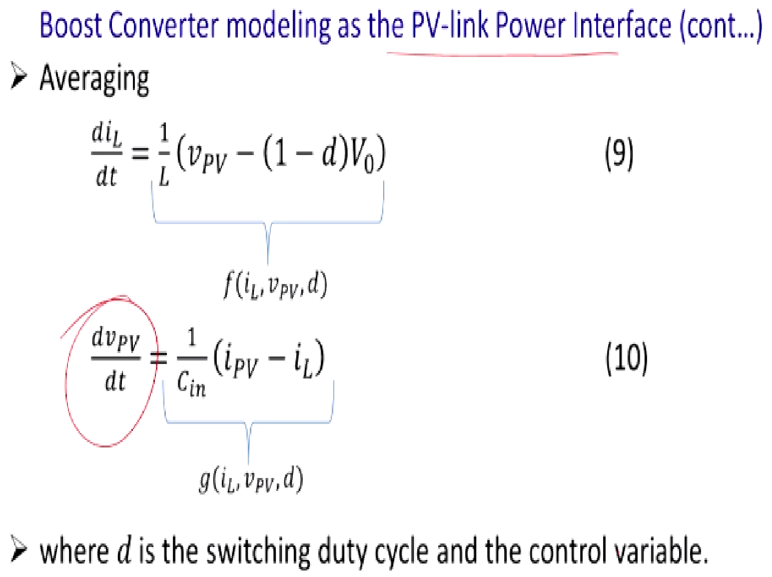

Boost Converter modeling as the PV-link Power Interface (cont...)

- Averaging

$$\frac{di_L}{dt} = \underbrace{\frac{1}{L}(v_{PV} - (1-d)V_0)}_{f(i_L, v_{PV}, d)} \qquad (9)$$

$$\frac{dv_{PV}}{dt} = \underbrace{\frac{1}{C_{in}}(i_{PV} - i_L)}_{g(i_L, v_{PV}, d)} \qquad (10)$$

- where d is the switching duty cycle and the control variable.

So, we should choose the average model here. We have a different kind of modeling. So, we will analyse here by the choosing the average model. The boost converter modeling in the PV link power interface is dL/dt = essentially 1/L PV-1-d x v0 and this what you have preferred, please go back you know we have referred here this this is the function and here this del f is this.

So, this will be abbreviated, was abbreviated there, so that Ldi/dt equal to is a function of iL PV and d and thus it is link 1/L PV-1-1d x v0. Similarly, this ripple of the voltage in the input side of the converter, that is the dv/dt is Cin iPV-iL, so where d is the switching frequency of the control variable.

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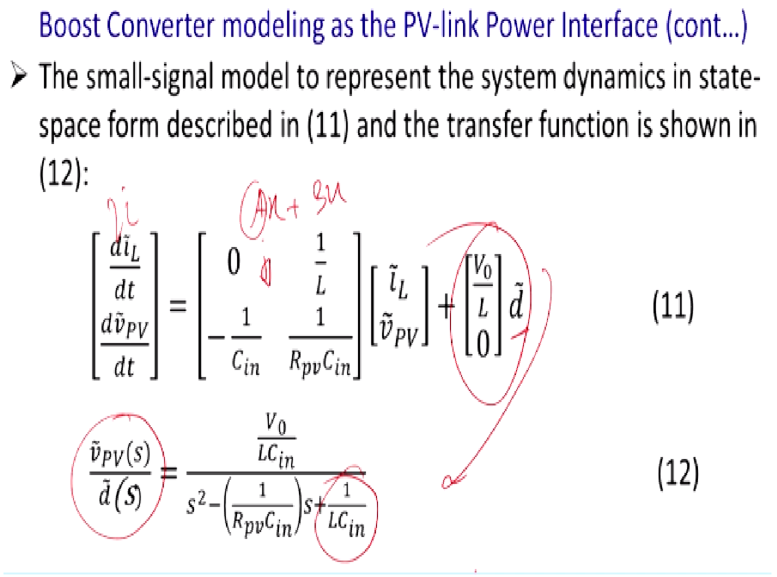

Boost Converter modeling as the PV-link Power Interface (cont...)

- The small-signal model to represent the system dynamics in state-space form described in (11) and the transfer function is shown in (12):

Ax+ Bu

$$\begin{bmatrix} \frac{d\tilde{i}_L}{dt} \\ \frac{d\tilde{v}_{PV}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{L} \\ -\frac{1}{C_{in}} & \frac{1}{R_{pv}C_{in}} \end{bmatrix} \begin{bmatrix} \tilde{i}_L \\ \tilde{v}_{PV} \end{bmatrix} + \begin{bmatrix} \frac{V_0}{L} \\ 0 \end{bmatrix} \tilde{d} \qquad (11)$$

$$\frac{\tilde{v}_{PV}(s)}{\tilde{d}(s)} = \frac{\frac{V_0}{LC_{in}}}{s^2 - \left(\frac{1}{R_{pv}C_{in}}\right)s + \frac{1}{LC_{in}}} \qquad (12)$$

Thus you can write the state-space equations. So, converter's modeling of the PV link, so small signal model represents the system dynamics in steady in state-space descriptions in equation 11 and you can convert it to that transfer functions. So, it is A matric and this is a B matrix, you know how to convert state-space to the transfer function. So, this is a state-space, that is Ldi/dt equal and these are the essential x dot. This is your Ax+Bu, so this is the A matrix essentially and this is the U matrix where U here is the change in the duty cycle.

So the transfer functions, what you can find here is that v delta PV that is the voltage change with the change of the duty cycle, if you have large scale, you can remove also the delta. So, essentially you are left with v0/LCin that is the capacitor input capacitor and just second order system, that is that is what we familiar. If it is a second order system, we can analyse it quite good, so s square – 1/Rpv x Cn x s + natural frequency of oscillations comes out from the L and the capacitor input.

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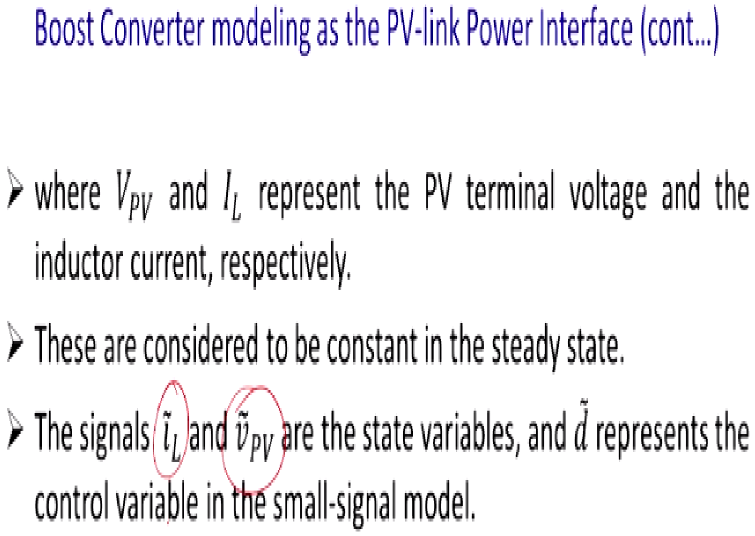

Boost Converter modeling as the PV-link Power Interface (cont...)

- where V_{PV} and I_L represent the PV terminal voltage and the inductor current, respectively.
- These are considered to be constant in the steady state.
- The signals $\tilde{i}_L$ and $\tilde{v}_{PV}$ are the state variables, and $\tilde{d}$ represents the control variable in the small-signal model.

So, from this what we can say is that where the PV and the IL represents the terminal voltage and the inductor current respectively. These are considered to be constant in the state. The signals iL and Vpv are the state variable and d represents that control variable in the small-signal model.

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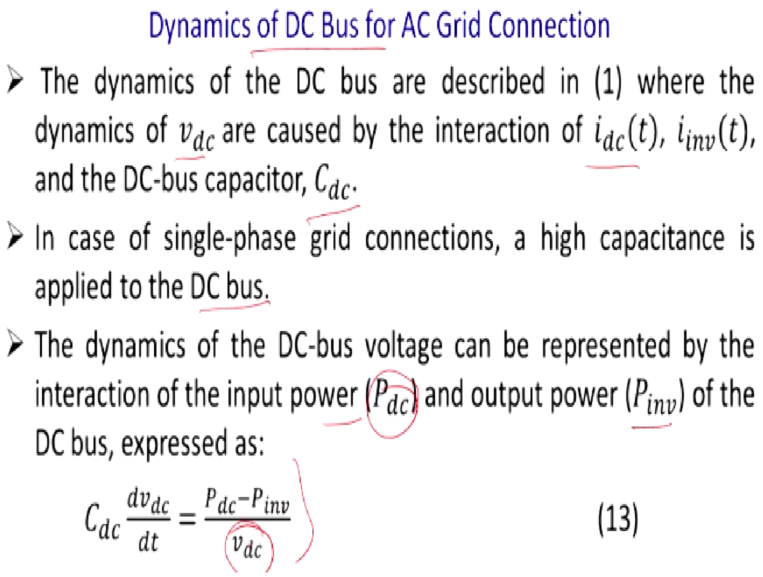

Dynamics of DC Bus for AC Grid Connection

- The dynamics of the DC bus are described in (1) where the dynamics of v_{dc} are caused by the interaction of $i_{dc}(t)$, $i_{inv}(t)$, and the DC-bus capacitor, C_{dc}.
- In case of single-phase grid connections, a high capacitance is applied to the DC bus.
- The dynamics of the DC-bus voltage can be represented by the interaction of the input power (P_{dc}) and output power (P_{inv}) of the DC bus, expressed as:

$$C_{dc}\frac{dv_{dc}}{dt} = \frac{P_{dc}-P_{inv}}{v_{dc}} \qquad (13)$$

Now, let us take a next case that is the dynamics of the DC bus for the AC grid connection, that when you are connecting to the main grid and you are converting the power DC to AC, and thus what happened? This dynamics of this DC bus is described, please refer to the equation 1 where the dynamics of Vdc is caused by interaction between idc that is the current, it is generated from the PVSC and the inverter, the current sink into this grid-side converter and the DC bus capacitor Cdc.

In case of the single-phase grid connections, a cap a high capacitance is applied to the DC bus. So that what happened, you have you have a less disturbance. The dynamics of the DC bus voltage can be represented by the interactions of the input power Pdc and the output power essentially what we since it is an AC so you are mentioning at Pinv of the DC bus. So, we can write, rewrite in terms of Cdv/dt, so with the suffix dc that is Pdc-inv by the voltage dc. So, you can equate in terms of power. So, essentially Cdv/dt = I, so I can be written as a difference of the power by the voltage.

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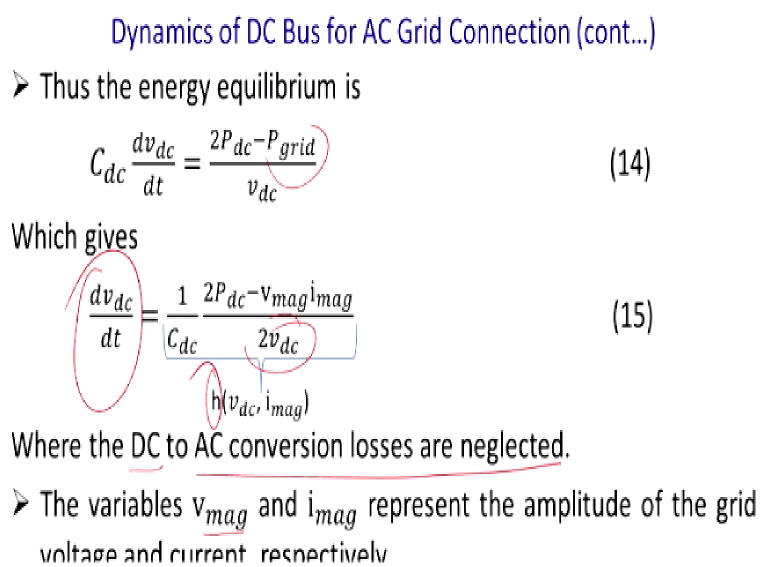

Dynamics of DC Bus for AC Grid Connection (cont...)

- Thus the energy equilibrium is

$$C_{dc}\frac{dv_{dc}}{dt} = \frac{2P_{dc}-P_{grid}}{v_{dc}} \qquad (14)$$

Which gives

$$\frac{dv_{dc}}{dt} = \underbrace{\frac{1}{C_{dc}}\frac{2P_{dc}-v_{mag}i_{mag}}{2v_{dc}}}_{h(v_{dc},\, i_{mag})} \qquad (15)$$

Where the DC to AC conversion losses are neglected.

- The variables v_{mag} and i_{mag} represent the amplitude of the grid voltage and current respectively

Thus what happened in the energy equilibrium, so Cdv/dt = 2Pdc-Pgrid/Vdc where this one you can rewrite as you know this is 1/Cdc x 2Pdc- this can be split it into the v and I grid-side voltages and current by the the DC bus voltage that is 2VC and that we name it as a function hVdc and img max, where the DC and the AC conversion losses, we assume that the system is lossless here. So, the variable this v magnitude mag and imag represents the amplitude of the grid voltage and current respectively.

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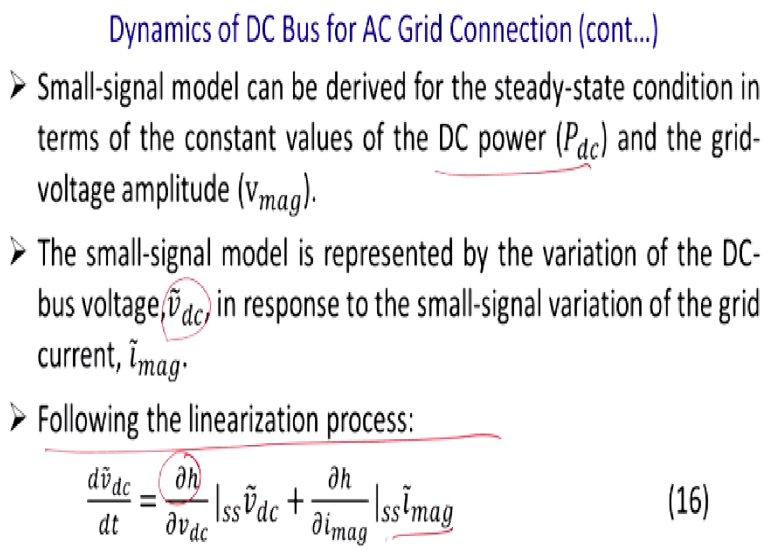

Dynamics of DC Bus for AC Grid Connection (cont...)

- Small-signal model can be derived for the steady-state condition in terms of the constant values of the DC power (P_{dc}) and the grid-voltage amplitude (v_{mag}).
- The small-signal model is represented by the variation of the DC-bus voltage, $\tilde{v}_{dc}$, in response to the small-signal variation of the grid current, $\tilde{i}_{mag}$.
- Following the linearization process:

$$\frac{d\tilde{v}_{dc}}{dt} = \frac{\partial h}{\partial v_{dc}}\Big|_{ss}\tilde{v}_{dc} + \frac{\partial h}{\partial i_{mag}}\Big|_{ss}\tilde{i}_{mag} \qquad (16)$$

Now, what we can say, so again we can go for the same treatment for small-signal operation. So, here the small-signal model can be derived for the steady-state condition in terms of the constant value of the DC power Pdc and the grid amplitude Vmag. The small-signal model represented by a variation of the Vdc bus voltage that is v delta in response to the small signal variations of the grid current Imag and thus we can apply the following linearization process and thus Vdc/dt = this h, please refer to the previous side what is h you know by Vdc is the steady-state value dc + hig magnitude ss imag.

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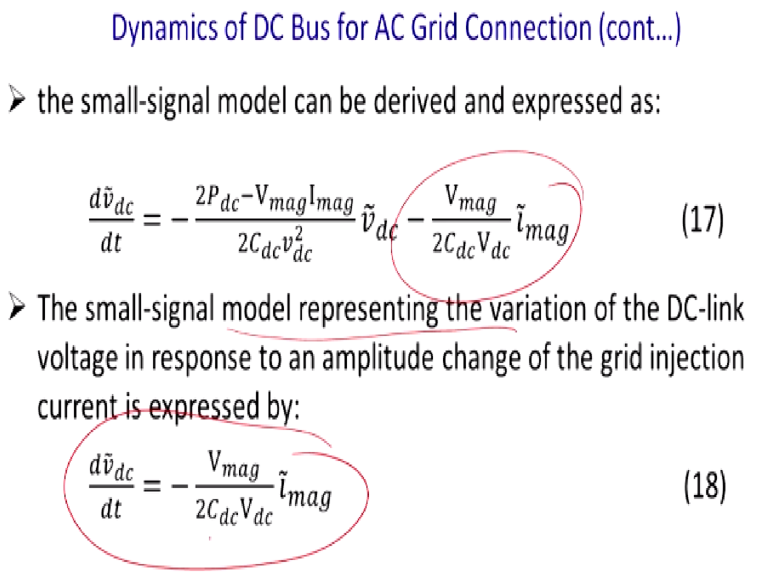

Dynamics of DC Bus for AC Grid Connection (cont...)

- the small-signal model can be derived and expressed as:

$$\frac{d\tilde{v}_{dc}}{dt} = -\frac{2P_{dc}-V_{mag}I_{mag}}{2C_{dc}v_{dc}^2}\tilde{v}_{dc} - \frac{V_{mag}}{2C_{dc}V_{dc}}\tilde{\imath}_{mag} \qquad (17)$$

- The small-signal model representing the variation of the DC-link voltage in response to an amplitude change of the grid injection current is expressed by:

$$\frac{d\tilde{v}_{dc}}{dt} = -\frac{V_{mag}}{2C_{dc}V_{dc}}\tilde{\imath}_{mag} \qquad (18)$$

The small-signal model can be derived and can express as dvdc/dt = -Pdc-Vmag x Imag/2dcv square dc – this terms V magnitude 2dc x Vdc imag. The small-signal model representing the variation in the DC link voltage in response to the multiple changes in the grid injection current is expressed by Vdc/dt = -Vmag 2Cdc imag. So, this will be your the voltage ripple into the capacitor of this input to that grid-side inverter.

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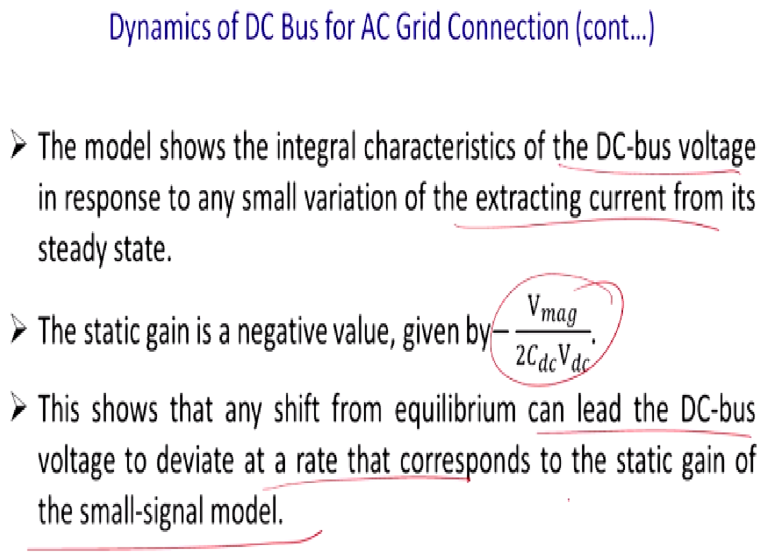

Dynamics of DC Bus for AC Grid Connection (cont...)

- The model shows the integral characteristics of the DC-bus voltage in response to any small variation of the extracting current from its steady state.
- The static gain is a negative value, given by $-\frac{V_{mag}}{2C_{dc}V_{dc}}$.
- This shows that any shift from equilibrium can lead the DC-bus voltage to deviate at a rate that corresponds to the static gain of the small-signal model.

Thus what we can say the model shows that the integral characteristics of the DC bus voltage in res in response to the any small variation in extracting the current form its steady state steady state and thus what happened, the steady state gain is negative value and is given by the minus Vmag/2CdcVdc. This allows that any shift from the equilibrium can lead to the DC bus voltage to deviate at a rate that corresponds to the static gain of the small-signal model, so that is something we require to keep in mind.

So, this is the some takeaway of this modeling that this shows any shift from the equilibrium point can lead to the DC bus voltage to deviate at a rate that corresponding to the static gain of the small-signal model. So you can know you can be sure that at which rate this change is occurring. Thank you. Thank you for your attention. We shall continue in a modeling of other converter in our next class.