DC Microgrid and Control System
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Lecture - 30
DC Microgrid Dynamics and Modeling (Continued)

Welcome to our NPTEL course on the DC microgrid and the Control System. Today, we are going to discuss this dynamics of the DC microgrid and its modeling. We were continuing with the grid-side modeling now.

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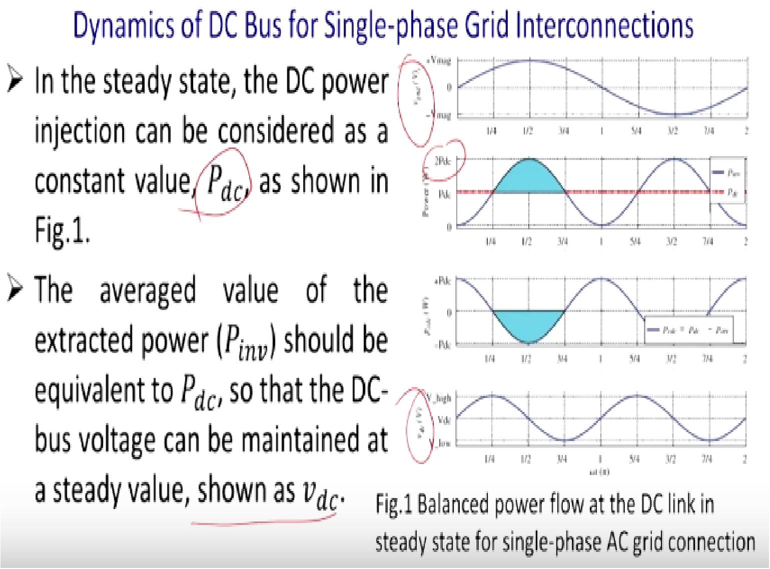

Dynamics of DC Bus for Single-phase Grid Interconnections

- In the steady state, the DC power injection can be considered as a constant value, P_{dc}, as shown in Fig.1.
- The averaged value of the extracted power (P_{inv}) should be equivalent to P_{dc}, so that the DC-bus voltage can be maintained at a steady value, shown as v_{dc}.

Fig.1 Balanced power flow at the DC link in steady state for single-phase AC grid connection

Now we shall now take it out the dynamics of the DC bus for single-phase grid connected inverter, most time most of the thing it is placed in our domestic appliances. So what happened, this is the grid-side voltage that is a maximum voltage Vmax and ultimately the power is your, this is the average power and this is the double of the power, and I am coming to you why it is so because of this why it is that oscillations is there.

So here, you can see that this blue one is the inverter power and this is the average power and also inverter power can be positive negative uh for the for the timing being and thus what happened, you know this is the DC power, so there will be a ripple in the DC power. So, in the steady state, that DC power injection is considered as a constant value Pdc as shown in the figure 1. So, this is the red line.

The average value of the extracted power P inverter should be equivalent to the Pdc that is what the the scenario, so that the DC bus voltage can be maintained at the steady state value as shown in Vdc, but what happened for the reference of the sorry.

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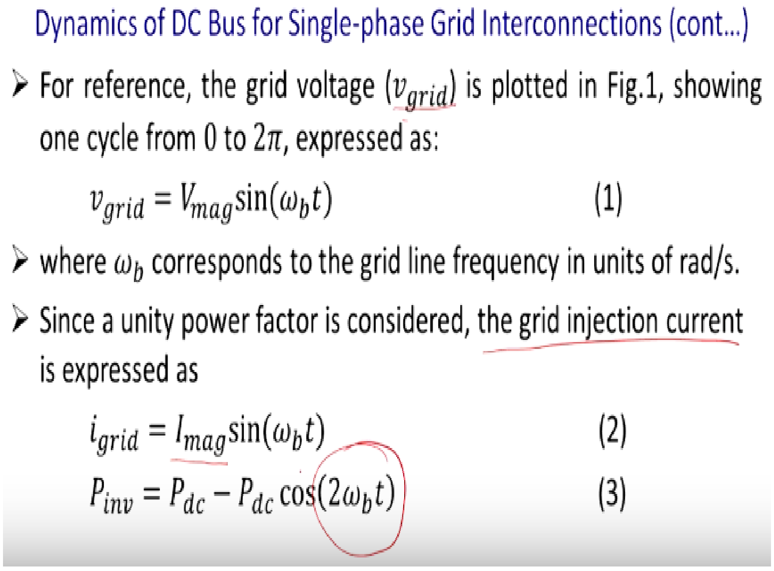

Dynamics of DC Bus for Single-phase Grid Interconnections (cont...)

- For reference, the grid voltage (v_{grid}) is plotted in Fig.1, showing one cycle from 0 to 2π, expressed as:

$$v_{grid} = V_{mag}\sin(\omega_b t) \qquad (1)$$

- where ω_b corresponds to the grid line frequency in units of rad/s.
- Since a unity power factor is considered, the grid injection current is expressed as

$$i_{grid} = I_{mag}\sin(\omega_b t) \qquad (2)$$

$$P_{inv} = P_{dc} - P_{dc}\cos(2\omega_b t) \qquad (3)$$

So for the reference of the grid voltage that is Vgrid and it is plotted 1 and it is showing that whole cycle of 0 to 2pi why grid voltage is essentially Vmax or V magnitude x sine Omega T where omega b represents that grid frequency which is in radiant per second since the unity power factor is considered that is the operation we will consider here the grid injection current is expressed as a pure sinusoid without any harmonics. So, I grid = Imag sine omega t/Pinv Pdc uh Pdc – Pdc cos of double frequency oscillations, which we have seen there.

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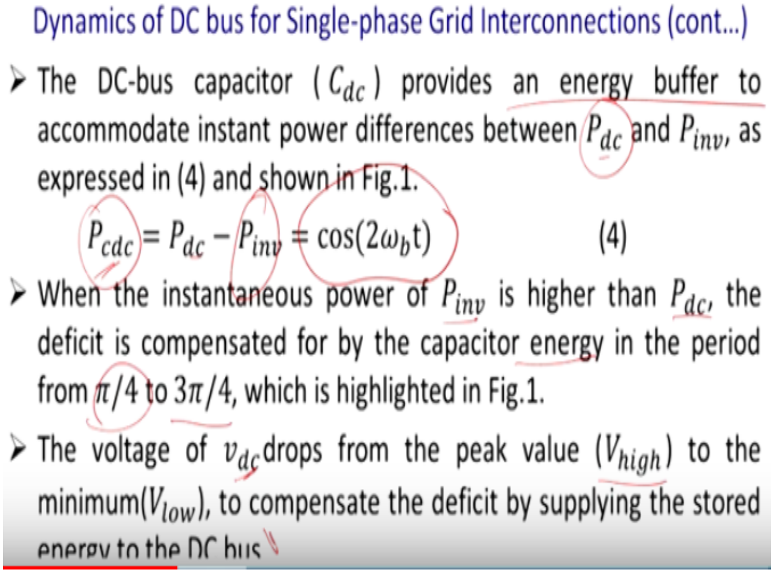

Dynamics of DC bus for Single-phase Grid Interconnections (cont...)

- The DC-bus capacitor (C_{dc}) provides an energy buffer to accommodate instant power differences between P_{dc} and P_{inv}, as expressed in (4) and shown in Fig.1.

$$P_{cdc} = P_{dc} - P_{inv} = \cos(2\omega_b t) \qquad (4)$$

- When the instantaneous power of P_{inv} is higher than P_{dc}, the deficit is compensated for by the capacitor energy in the period from $\pi/4$ to $3\pi/4$, which is highlighted in Fig.1.
- The voltage of v_{dc} drops from the peak value (V_{high}) to the minimum(V_{low}), to compensate the deficit by supplying the stored energy to the DC bus

So what happened that is the instead there will be a DC value along width there will be oscillatory value because if you multiply essentially to sine you will get essentially sine square omega t you can split 1 - 2 cos omega t/2, so essentially what one part is your or DC another part is your double frequency oscillation and that double frequency oscillation over a period of the time of the 2 cycle over the period of the time of this 1 cycle it is zero since it is double frequency, but instantaneously there will be a DC component above it that is what I have shown in the figure number 1.

Above it there will be oscillation of the double frequency power and thus that DC capacitor Cdc provides an energy buffer to accommodate the instant difference between the, so that is the cause of the inv and the difference between the Pc and inv as expressed in this next equation for in the and if it can be shown in the figure 1, you can refer back to the slide number 1 by dragging. so Pcdc there is a capacitor power essentially it has a Pdc that has been fed by this by this DC to DC converter minus Pinv.

Essentially will have a double frequency oscillation and sometime it will be positive sometime it will be negative so this has to be supplied or by this capacitor. When the instantaneous power Pinv is is higher than the Pdc that def this deficit is compensated by the capacitor energy, so ultimately capacitor will discharge and that will feed that extra power in the period, so please refer back to the figure number 1, I cannot refer back every instant , so form pi/4 to 3 pi/4, which is highlighted in figure 1.

I just show for one reference, please captured it, so this is the point has been marked here as a blue name, so you got a Pinv be more than the Pdc. The voltage of this of this Vdc drops from the peak value high to the minimum low to compensate that compensate the deficit by supplying the stored energy of the DC bus.

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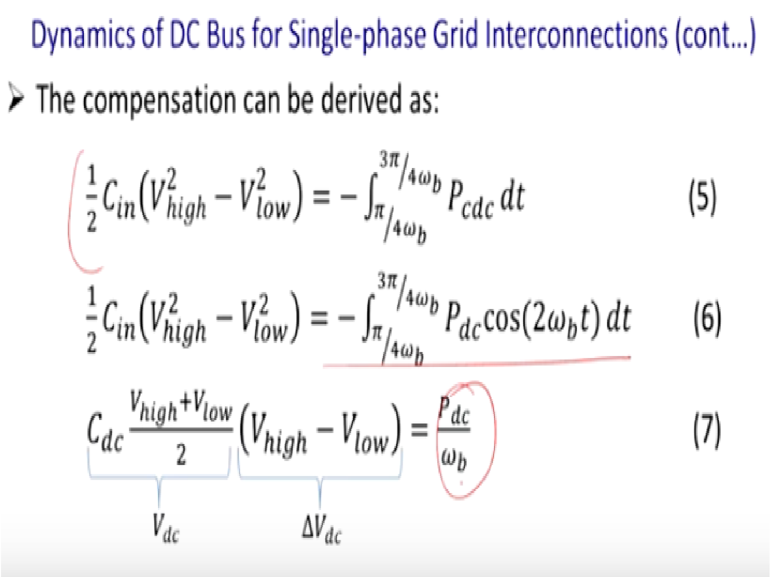

Dynamics of DC Bus for Single-phase Grid Interconnections (cont...)

- The compensation can be derived as:

$$\frac{1}{2}C_{in}\left(V_{high}^2 - V_{low}^2\right) = -\int_{\pi/4\omega_b}^{3\pi/4\omega_b} P_{cdc}\,dt \qquad (5)$$

$$\frac{1}{2}C_{in}\left(V_{high}^2 - V_{low}^2\right) = -\int_{\pi/4\omega_b}^{3\pi/4\omega_b} P_{dc}\cos(2\omega_b t)\,dt \qquad (6)$$

$$C_{dc}\underbrace{\frac{V_{high}+V_{low}}{2}}_{V_{dc}}\underbrace{\left(V_{high} - V_{low}\right)}_{\Delta V_{dc}} = \frac{P_{dc}}{\omega_b} \qquad (7)$$

So we required to compensate the designs or we require a compensator, essentially capacitor is a compensator and thus so 1/2 CV square essentially this equations, so 1/2 Cin V square high - VI square low is the difference between the variation of the input of the capacitor of the dis of this before this grid side converter and that can be minus pi/4 by 3pi/4 Pdcdt, similarly 1/2 Cin V square - V low square is given by the same value pi/4 to 3pi/4 and thus you can multiply this this capacitor and this voltage.

Essentially these 2 voltages will give you that power/time, that will be Pdc/omega and it will be essentially pdc the he rate of change of power that will be fed from the system.

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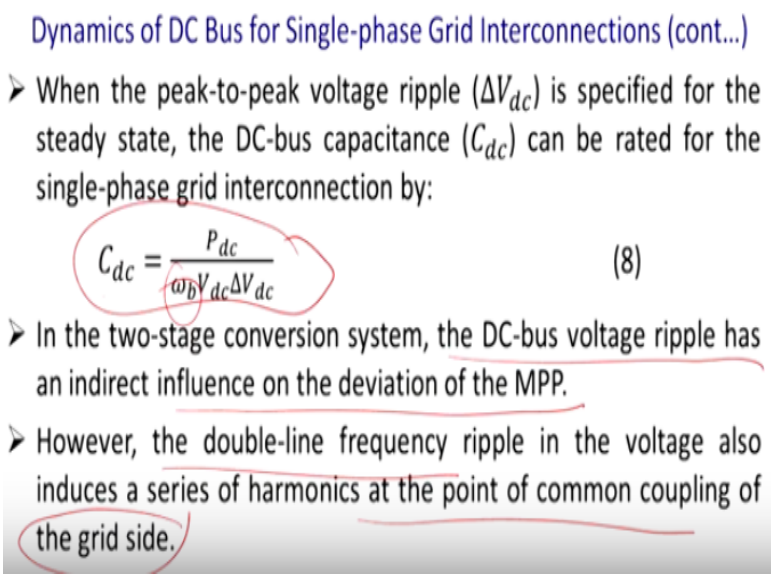

Dynamics of DC Bus for Single-phase Grid Interconnections (cont...)

- When the peak-to-peak voltage ripple (ΔV_{dc}) is specified for the steady state, the DC-bus capacitance (C_{dc}) can be rated for the single-phase grid interconnection by:

$$C_{dc} = \frac{P_{dc}}{\omega_b V_{dc}\Delta V_{dc}} \qquad (8)$$

- In the two-stage conversion system, the DC-bus voltage ripple has an indirect influence on the deviation of the MPP.
- However, the double-line frequency ripple in the voltage also induces a series of harmonics at the point of common coupling of the grid side.

So, we have to take different kind of conditions. There is dynamics of the DC bus in for the single phase interconnections, where in a same thing definitely, when peak-to-peak voltage ripple Vdc is specified for the steady state that you should have this much of that DC link voltage and the DC bus capacitor Cdc can be rated for the single-phase grid connections and ultimately this will be given by this. So Cdc Pdc omega Vdc x del Idc.

So mind it so if you are using one solar inverter which has been designed for the 60 years and if you wish to design in 50 years, then we require to change the value of the capacitor, otherwise what we will find that this ripple will be more. They in the two-stage conversion system, the DC bus voltage ripple has an indirect influence for deriving the MPPT because it will naturally change the MPPT point, these oscillations. Thus, your tracker unnecessarily has to run and track that MPPT point and ultimately it cannot it is changing so fast may not able to converge and it is a line frequency.

So, for this reason, it is 100 Hertz for the 50 year system. However the double-frequency ripple in the voltage also induces a series harmonics at that point of common coupling of the grid side, that is quite dangerous, it is an even harmony and you know that even harmony is generally not there because of the symmetry of the Fourier series and this double-frequency oscillation will inject and the double-frequency power in a point of common coupling.

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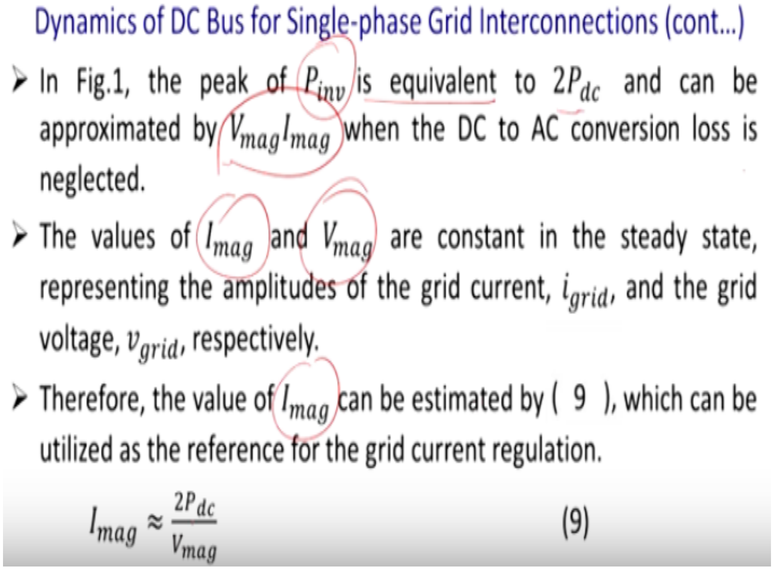

Dynamics of DC Bus for Single-phase Grid Interconnections (cont...)

- In Fig.1, the peak of P_{inv} is equivalent to $2P_{dc}$ and can be approximated by $V_{mag}I_{mag}$ when the DC to AC conversion loss is neglected.
- The values of I_{mag} and V_{mag} are constant in the steady state, representing the amplitudes of the grid current, i_{grid}, and the grid voltage, v_{grid}, respectively.
- Therefore, the value of I_{mag} can be estimated by (9), which can be utilized as the reference for the grid current regulation.

$$I_{mag} \approx \frac{2P_{dc}}{V_{mag}} \quad (9)$$

So thus, what happens? The dynamic so what we have shown in the figure 1 the peaks of the inv is at 2Pdc, which you can refer back to the figure, and can be approximated by the multiplication of the Imag and Vmag because if you are feeding a resistive load, then that kind of conditions comes. So, once you have a voltage peak, current is also the peak, and thus you are taking huge amount of current and the power from this capacitor.

When the DC to AC conversion occurs, you have neglected the losses of the converter. The values of Imag or the maximum or Vmag are the constant in the steady state representing the amplitude of the grid current igrid and the grid voltage vgrid respectively. Therefore, the value Imag is estimated by the equations I shall show later, which can be which can be utilized as a reference for the grid regulation, this equation will be 9. So Imag= essentially 2Pdc/Vmag.

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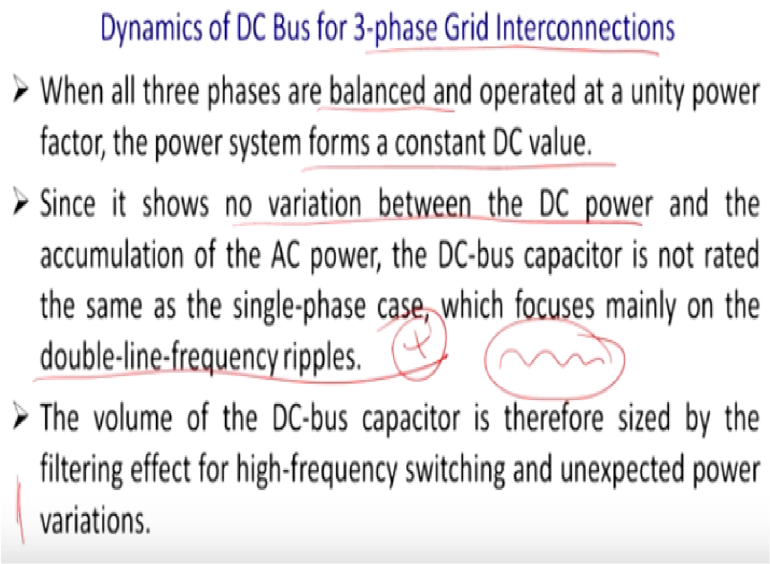

Dynamics of DC Bus for 3-phase Grid Interconnections

- When all three phases are balanced and operated at a unity power factor, the power system forms a constant DC value.
- Since it shows no variation between the DC power and the accumulation of the AC power, the DC-bus capacitor is not rated the same as the single-phase case, which focuses mainly on the double-line-frequency ripples.
- The volume of the DC-bus capacitor is therefore sized by the filtering effect for high-frequency switching and unexpected power variations.

So, the dynamics of this DC bus 3-phase grid interconnections, we can see another few interesting aspects. For the 3 phases, there will be few things more. When all the 3 phases are balanced hopefully and operated at unity power factor, the power system forms a constant DC value, so that is a one of the important features. Since it shows no variation between the DC power and the accumulations of the AC power, the DC bus capacitor is not rated at the same as the single-phase case, which focuses mainly on the double-frequency ripple, that is something quite important in case of the 3-phase system.

So you have the DC bus capacitor is not rated as in case of the single-phase case and which is only focuses on the double-frequency oscillations and thus what happen, the value of the since you have a ripple of like this, this will be a 6 pulse converter instead of the double frequency, it the frequency will be sixth harmonics, it is 300 Hertz or the 360 Hertz, depending on the your system and thus the size of the capacitor will be reduced.

The volume of the DC bus capacitor therefore is their capacitor is therefore sized by the filtering effect of the high frequency switching and unexpected power variation. So thus, you know using using a 3 -phase system inherently has an advantage over the single-phase system, what depends you know whether you are connected to your PV or whether your power evacuation is done by the single-phase or three-phase that depends on the rating. So generally, up to 5 kV, we generally allow single phase, above that, we allow the three phase.

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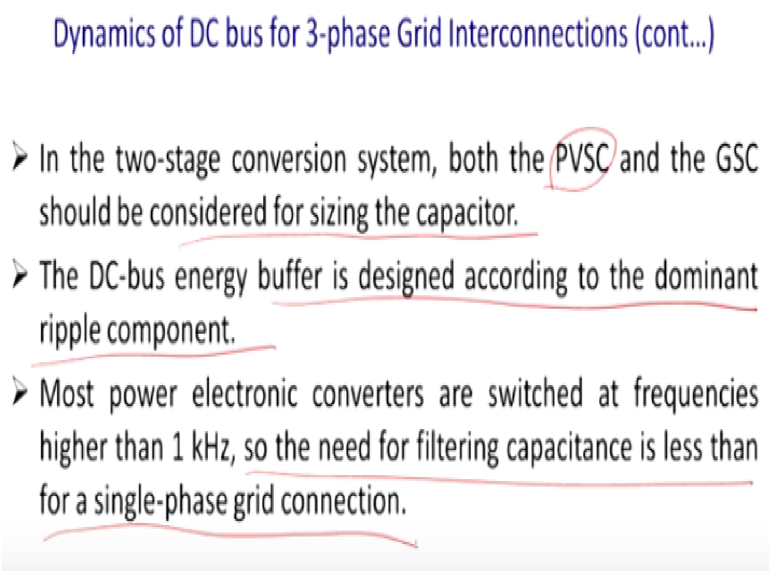

Dynamics of DC bus for 3-phase Grid Interconnections (cont...)

- In the two-stage conversion system, both the PVSC and the GSC should be considered for sizing the capacitor.
- The DC-bus energy buffer is designed according to the dominant ripple component.
- Most power electronic converters are switched at frequencies higher than 1 kHz, so the need for filtering capacitance is less than for a single-phase grid connection.

So in case of the two-stage conversion system, the both the PV side converter and the grid side converter, we can consider for the sizing the capacitor, so we require to design this capacitor value quite well, otherwise there might be a drop of the voltages and all those things. The DC bus energy buffer is designed according to the dominant ripple component, so that is also we required to keep in mind, whether if it is a three-phase, so it will be a sixth harmonic, if it is a single phase, it will be the second harmonic.

For example, you know most power electronics converters switched at a frequency higher than 1 kilohertz, so the need of the filtering capacitor is less than for a single-phase grid connections, so that is the attribution you can make it.

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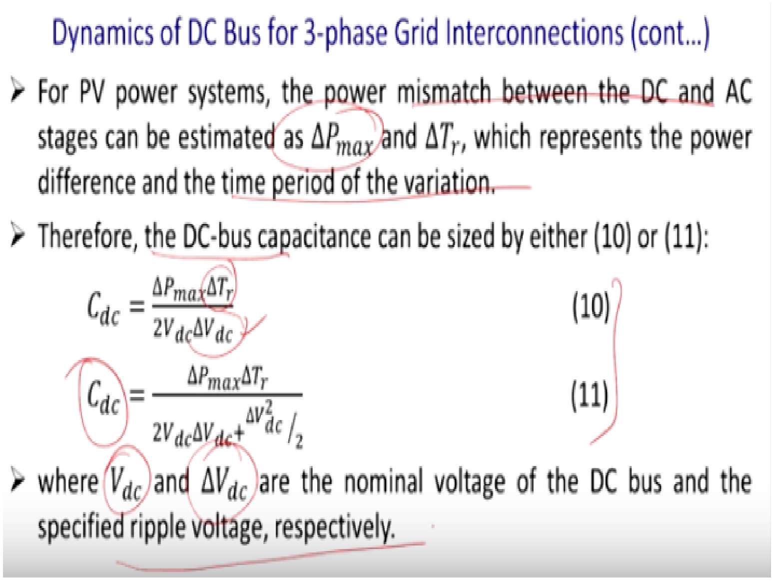

Dynamics of DC Bus for 3-phase Grid Interconnections (cont...)

- For PV power systems, the power mismatch between the DC and AC stages can be estimated as ΔP_{max} and ΔT_r, which represents the power difference and the time period of the variation.
- Therefore, the DC-bus capacitance can be sized by either (10) or (11):

$$C_{dc} = \frac{\Delta P_{max}\Delta T_r}{2V_{dc}\Delta V_{dc}} \tag{10}$$

$$C_{dc} = \frac{\Delta P_{max}\Delta T_r}{2V_{dc}\Delta V_{dc} + \Delta V_{dc}^2/2} \tag{11}$$

- where V_{dc} and ΔV_{dc} are the nominal voltage of the DC bus and the specified ripple voltage, respectively.

So let us go for the design of this capacitor bus for the three-phase system, For PV power system, the power mismatch between DC and the AC stages can be estimated as del P max and del Tr, which represents the power difference and that time period of the variation. So that is something we required to keep in mind, so where it is match, where it is mismatch. Therefore, since it is 6 pulse, it won't something like 90 degree, so we required to calculate and that time we will say that whether there is a mismatch occur, it is here.

So therefore the DC bus capacitance can be sized as shown in the this is equation so that is the power maximum that is I max into V max or the I magnitude x V magnitude into Tr for the duration where the power maximum has occurred and the 2Vdc x the ripple voltage of this Vdc. So lesser the capacitor value, lower will be the ripple in that way or you can predefine that ripple is 2%, 5%, accordingly you calculate the value of the capacitor.

So Cdc = P max x del Tr 2dc x del Vdc + del V square dc/2, where dc and del dc are the norm nominal voltages of the DC bus and thus specified ripple voltage.

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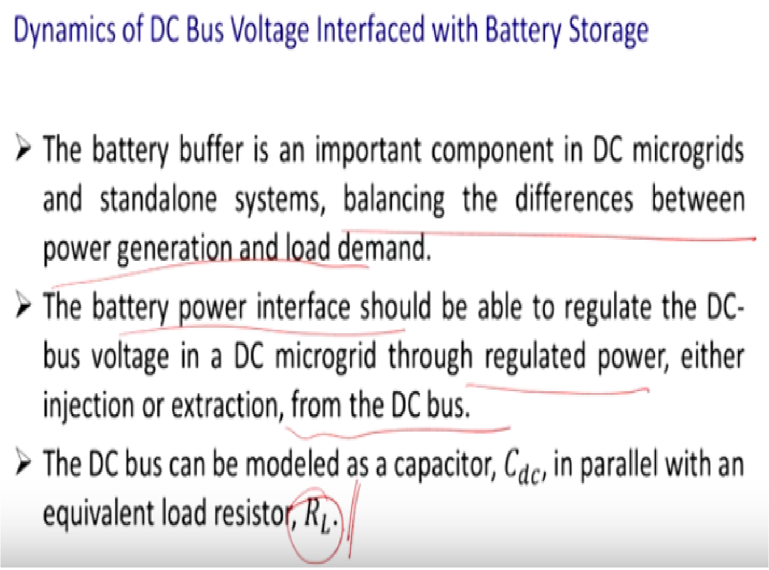

Dynamics of DC Bus Voltage Interfaced with Battery Storage

- The battery buffer is an important component in DC microgrids and standalone systems, balancing the differences between power generation and load demand.
- The battery power interface should be able to regulate the DC-bus voltage in a DC microgrid through regulated power, either injection or extraction, from the DC bus.
- The DC bus can be modeled as a capacitor, C_{dc}, in parallel with an equivalent load resistor, R_L.

The battery buffer is an important component in DC microgrid in a standalone system because most of the cases you may have a mismatch between the generation peak and the demand peak and also instantaneous mismatch between the power between the two entities, balancing the difference between these two generations and the load demand and thus what happen, the battery power interface should be able to regulate that DC voltage in a microgrid through regulated power, either injecting or extracting the power from the DC bus.

So once you have a mismatch between the power, so it will that extra power should come from the battery, once you have a surplus that power should go back to the battery, and over a period of time and also the double frequency case. Thus, what happens, the DC bus can be modeled as a capacitor Cdc in parallel with an equivalent load resistor RL, that is the way we can model for the microgrid application

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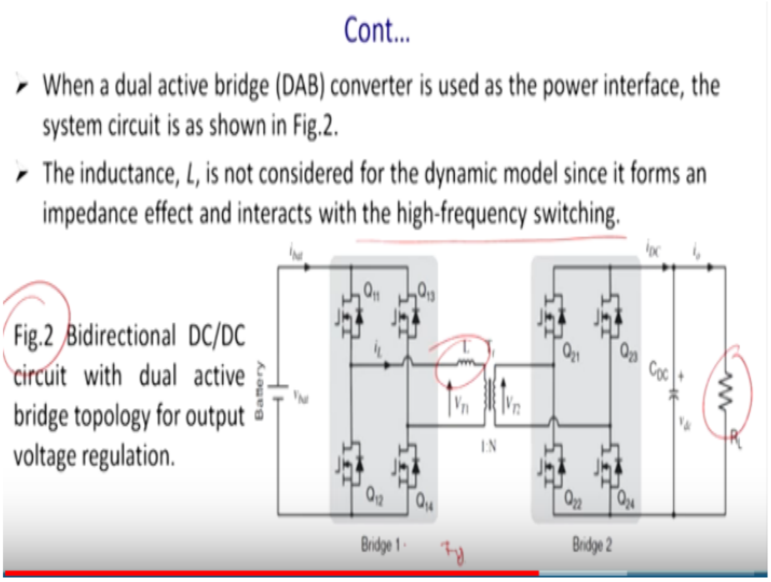

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- When a dual active bridge (DAB) converter is used as the power interface, the system circuit is as shown in Fig.2.
- The inductance, L, is not considered for the dynamic model since it forms an impedance effect and interacts with the high-frequency switching.

Fig.2 Bidirectional DC/DC circuit with dual active bridge topology for output voltage regulation.

Now this is active dual-bridge converter, we can have a bi-directional flow of power if required, if this is a resistive, definitely it cannot send back the power, but you know if it is some kind of regenerative or some other features, then it can be a bi direction. So the dual-active bridge converter is used for the power interface. The system circuit is shown in the figure 2, this is figure 2, the inductance L here is not considered for the dynamic modeling because it is a leakage inductance.

Since it forms an independent impedance effect and interacts with the high-frequency switching, so we shall neglect it, but in actual model we require to consider it while designing the control aspect of this topology because mostly it is a lump parameter it is a leakage inductance of this high frequency transformer. So you this is a bidirectional bridge configuration and you will be sending power from the battery to this load.

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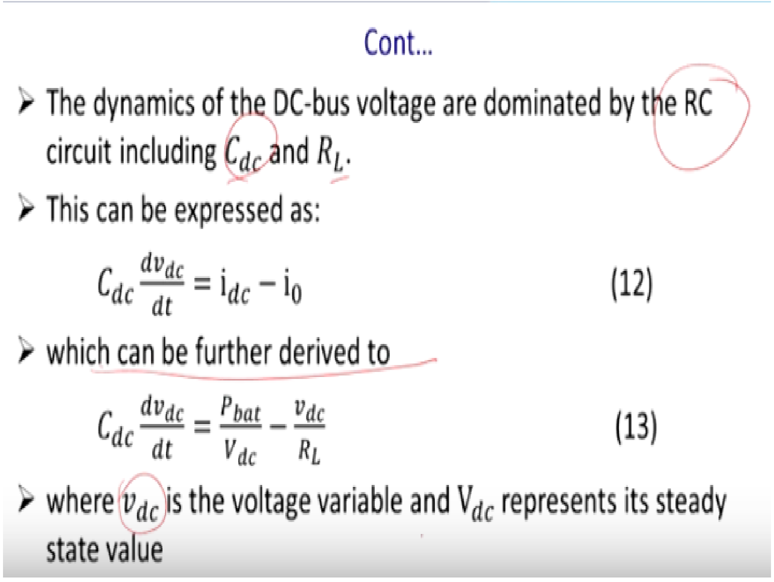

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- The dynamics of the DC-bus voltage are dominated by the RC circuit including C_{dc} and R_L.
- This can be expressed as:

$$C_{dc}\frac{dv_{dc}}{dt} = i_{dc} - i_0 \tag{12}$$

- which can be further derived to

$$C_{dc}\frac{dv_{dc}}{dt} = \frac{P_{bat}}{V_{dc}} - \frac{v_{dc}}{R_L} \tag{13}$$

- where v_{dc} is the voltage variable and V_{dc} represents its steady state value

What happened there, the dynamics of the DC bus voltage is dominated by this RC circuit that is including this Cdc and RL and this can be represented by CDC dv/dt = idc – i0 and which can be further derived into Cdc dv/dt = P battery/ DC - dc/RL where Vdc is the voltage variable and dc represents the steady state value.

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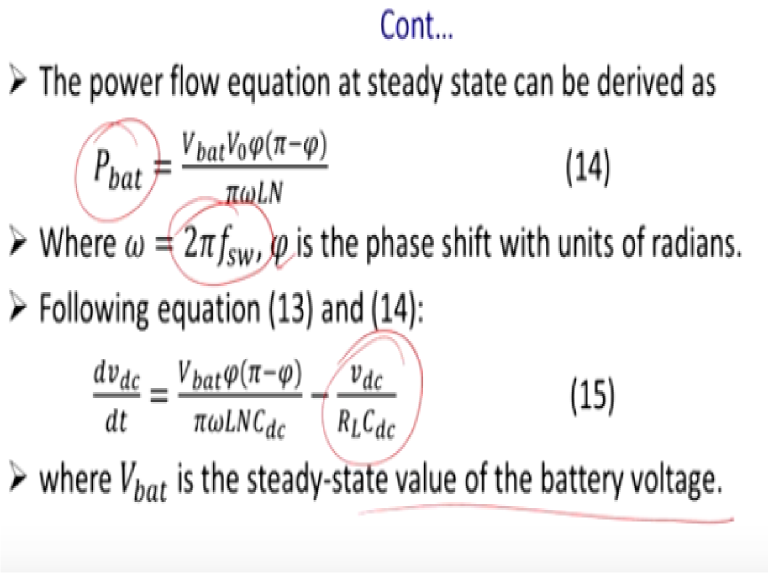

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- The power flow equation at steady state can be derived as

$$P_{bat} = \frac{V_{bat}V_0\varphi(\pi-\varphi)}{\pi\omega LN} \tag{14}$$

- Where $\omega = 2\pi f_{sw}$, φ is the phase shift with units of radians.
- Following equation (13) and (14):

$$\frac{dv_{dc}}{dt} = \frac{V_{bat}\varphi(\pi-\varphi)}{\pi\omega LNC_{dc}} - \frac{v_{dc}}{R_LC_{dc}} \tag{15}$$

- where V_{bat} is the steady-state value of the battery voltage.

From there what we can say is that the power flow equation at the steady state, so the whatever the power is flowing from the battery is battery voltage + output voltage x psi Pi - psi x 2 omega LN, where this omega is not a frequency of the grid, so it is quite fast, that is the frequency of this switching frequency of the converter that depends if it is a IGBT bus system thus using frequency can be tend to seams 5 kilohertz and psi is the phase shift between this unit in radians.

Thus what we can compute from this 13 and 14, so dv/dt = battery voltage x psi x pi-psi omega LNdc there will be a regulator factor VdcRL x Cdc where we assume that this battery voltage almost remains constant, so if there is no variation in the battery voltage, so our battery voltage is the steady state value of the battery, then only this analysis is more fruitful.

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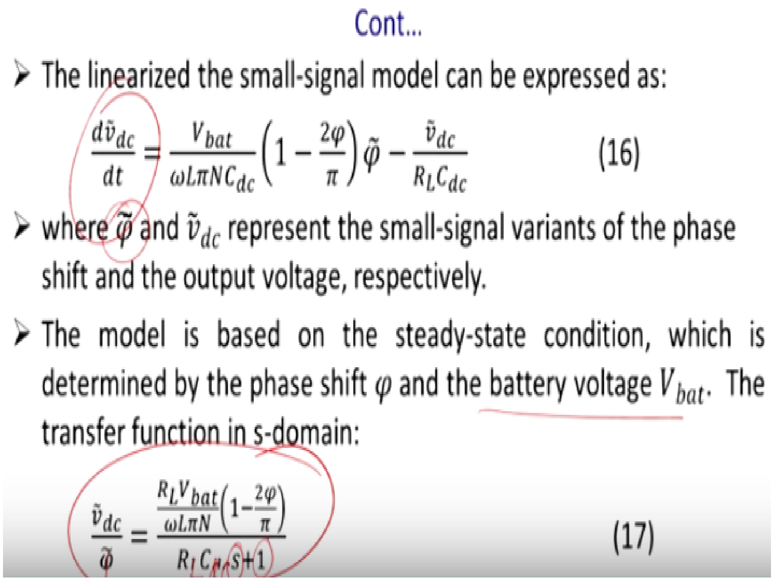

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- The linearized the small-signal model can be expressed as:

$$\frac{d\tilde{v}_{dc}}{dt} = \frac{V_{bat}}{\omega L \pi N C_{dc}}\left(1 - \frac{2\varphi}{\pi}\right)\tilde{\varphi} - \frac{\tilde{v}_{dc}}{R_L C_{dc}} \qquad (16)$$

- where $\tilde{\varphi}$ and $\tilde{v}_{dc}$ represent the small-signal variants of the phase shift and the output voltage, respectively.
- The model is based on the steady-state condition, which is determined by the phase shift φ and the battery voltage V_{bat}. The transfer function in s-domain:

$$\frac{\tilde{v}_{dc}}{\tilde{\varphi}} = \frac{\frac{R_L V_{bat}}{\omega L \pi N}\left(1 - \frac{2\varphi}{\pi}\right)}{R_L C_{dc} s + 1} \qquad (17)$$

So thus what happen, the linearized model of this DC to DC converter can be written in a form of ultimately from the statements, so del dt/dt = battery/ 2 omega omega L pi N where N is the number of trans ratio 1:N we have considered x Cdc 1-2psi-phi x psi minus this thing, this psi delta and Vdc delta essentially the variation of the phase and the variation of the DC bus voltage respectively.

The model is based on the steady-state condition which is determined by the phase shift phi and the battery voltage V battery and thus we can have a transfer function like this. So that is V delta dc/tau = RL battery omega LN omega L pi N/RL Cdc x s, si Laplace domain, + 1, so this will be the overall expressions of it and thus we can see that it is a first-order system unlike the second-order system which you have seen in the previous case.

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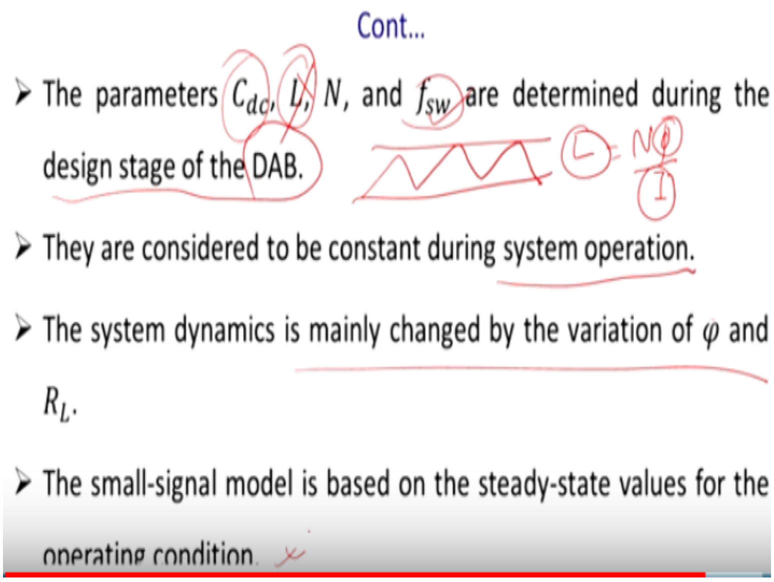

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- The parameters C_{dc}, L, N, and f_{sw} are determined during the design stage of the DAB.
- They are considered to be constant during system operation.
- The system dynamics is mainly changed by the variation of φ and R_L.
- The small-signal model is based on the steady-state values for the operating condition.

So, from this observation, we can say that the parameter, this capacitor voltage, this inductor which mostly we have neglected, the trans ratio and the switching frequency are determined for other designing stage of this this dual converter where you are. So they are considered to be the constant during the system operation. So, we will have a constant frequency operation so we cannot use hysteresis controller.

You know current is increasing, decreasing always in the inductor and thus this is the current through the inductor, this is the always you will find. You know that L = N Phi/I, so once current is it increasing but you make close to the saturation, thus your value of Phi may not be changing, thus you have a rollover effect. So value of this inductor will change according to the current, but that effect has been neglected and while considering that operation, we take the nominal value of the inductor, for actual operations, we have to take care of all those things.

They are considered to be the constant during the operations. The system dynamics is mainly changed by the variation of the psi and RL, so that is what we want to see and a small-signal model is based on the steady-state values for the operating condition and thus we can see that this converter is DC to DC converter works fine if you properly design this entities, that is Cdc, L and the switching frequency.

I have just 2-3 point to take away here in design aspect of here, just I just you know, so ultimately if you wish to design how you decide the switches that depends on the power handling capability of this DC to DC converter. If that the if this converter is IGBT, then it can handle the power up to the 100 kilowatt, and of course switching frequency required to be lower, and thus it is and ultimately you may be parallel operating also few converter, that also required to take into the account.

Ultimately while designing this, battery will give you the intermittent extra power required from the solar or this thing. So whatever solar is dis is taken and if it is a DC, then there is no problem, you can instantaneously feed this value, but if it is AC, solar and battery feeding a microgrid and there we will be instantaneous variations of the double frequency and maybe that current fed from this battery instead of this instead of instead of the load and thus bi-directional flow is possible and also may be that this capacitor itself can handle that power and can send back the power, then there will be a ripple in the capacitor.

Otherwise if it is feeding a DC system, so battery plus the grid will feed you the required load. Thank you. Thank you for your attention. I shall continue with the modeling in the next class also.