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

Lecture - 16
Microgrid Dynamics and Modeling

Welcome to our lectures on the DC Microgrid and Control system. We are going to discuss today the microgrid dynamics and modeling. This is one of the important part of the control of the DC microgrid.

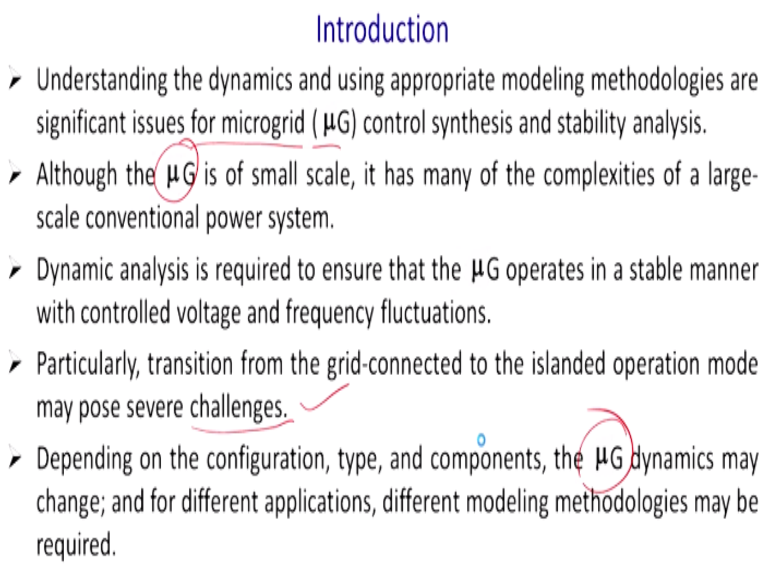
(Refer Slide Time: 01:00)

Contents

- Introduction
- Microgrid Structures
- Mathematical Analysis of Microgrid Structure
- DC Microgrids Dynamic Modeling
- Microsources Dynamics in DC Grid
- The DC Bus Dynamic Equation

So, our presentation layout will be introduction, thereafter microgrid structures, mathematical analysis of the microgrid structure, DC microgrid dynamic modeling, microsources dynamics in DC grid, the DC bus dynamic equation. These all will be discussed in detail in our discussions.

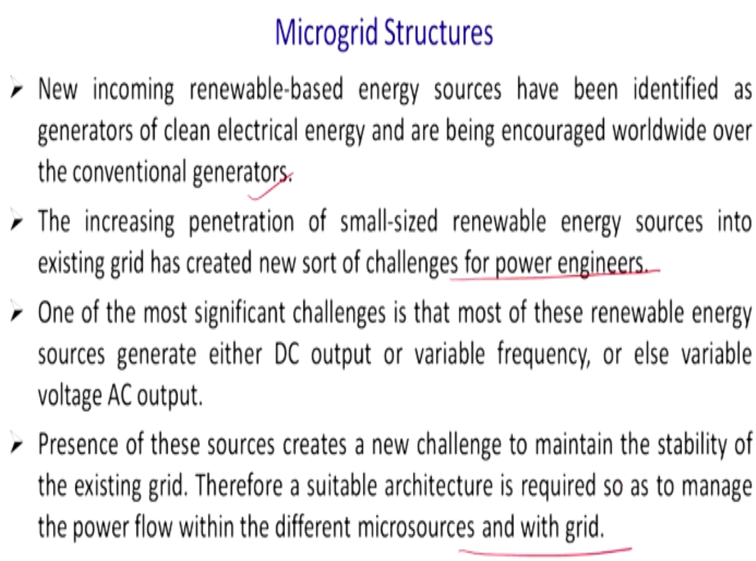
(Refer Slide Time: 01:10)



Understanding our dynamics and using appropriate modeling methods methodologies are significant issues for microgrid control synthesis and stability analysis. Although the microgrid is a small scale, it has many complexities of the large scale conventional power systems. The dynamic analysis is required to ensure that the microgrid appear as a stable manner, which control the voltage and the frequency fluctuations.

Particularly, transition from the grid connected to the islanding operation mode may pose several challenges, so we shall see that. Depending on the configurations, type, component, the microgrid dynamics may change and the different applications and different methodology may be applied or required.

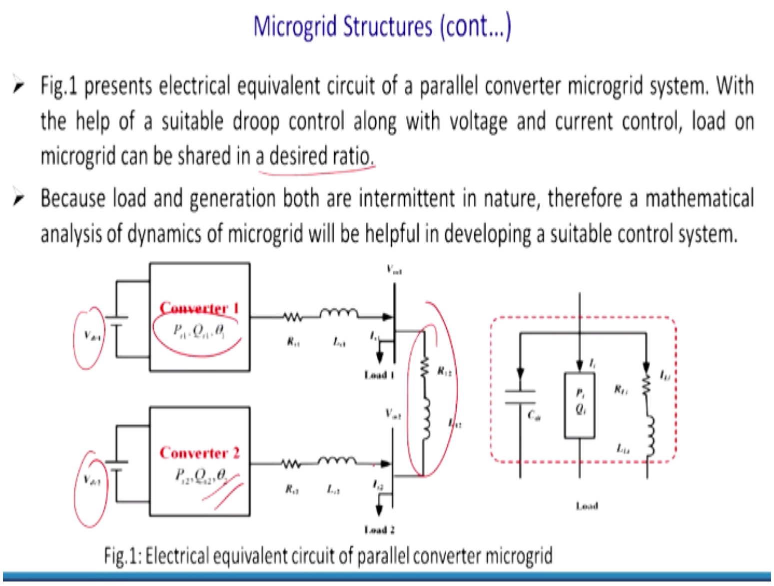
(Refer Slide Time: 02:20)



Now, incoming renewable-based energy sources has been identified as generator of the clean electrical energy and are being encouraged worldwide over that conventional generator because of the carbon footprint, global warming, and for many other issues. The increasing productions of small-sized renewable energy sources to existing grid has created a new sort of challenge for the power engineers. One of the most significant challenges is that this renewable energy sources generate either DC output or variable frequency or else variable voltage AC outputs.

So, you have seen that you know in case of the wind turbine that with a variable AC in case of the your DC, in case solar it is variable DC. In in presence of the sources create a new challenge to maintain the stability of the existing grid also when you connect the microgrid with a fundamental grid. Therefore suitable architecture is required to manage the power flow with the within the different microsources and the storage element and the load within grid.

(Refer Slide Time: 03:57)



So, for this reason, our figure 1 in this case represents the electrical equivalent circuits of a parallel converter microgrid system with the help of the suitable drop control along with the voltage and current, current control load on the microgrid can be shared in a desired ration. You have DC1 and DC2, so you can control over P real power, imaginary power and the phase angle.

Similarly, you can have a control over it and you can connect it to the same bus and ultimately you can say that these 2 buses can be internally connected and thus you can control the flow of power from this point to this point or this point to that point. Because of the load and generator both are intermittent in nature, previously load was intermittent in nature, now we have source also intermittent in nature; therefore, a mathematical analysis of dynamics of microgrid will be helpful to developing this suitable control system.

(Refer Slide Time: 05:24)

Mathematical Analysis of Microgrid Structure (cont...)

- A composite load has been assumed to be present as electrical load on microgrid, which consists of a linear, a nonlinear, and a constant power-type loads. The dynamics of these loads are presented as follows:
  - Linear load equations

$$V_{miq} = R_{Li}I_{Liq} + L_{Li}pI_{Liq} + \omega_{si}L_{Li}I_{Lid} \quad (5)$$

$$V_{mid} = R_{Li}I_{Lid} + L_{Li}pI_{Lid} - \omega_{si}L_{Li}I_{Liq} \quad (6)$$

  - Nonlinear load equation

$$I_{nonq} = \frac{2}{3}\frac{P_{inon}V_{miq} - Q_{inon}V_{mid}}{V_{mid}^2 + V_{miq}^2} \quad (7)$$

$$I_{nond} = \frac{2}{3}\frac{P_{inon}V_{mid} + Q_{inon}V_{miq}}{V_{mid}^2 + V_{miq}^2} \quad (8)$$

Dynamics of a parallel converter microgrid structures is shown in figure 1 is given as follows. The p denotes the differential function d/dt and i is the specific converter. Dynamics of the individual converter in d-q axis of the reference system is presented as Visq = miq + LsiqP x, this is the differential equations in the d-q axis. This is for q axis and this is for the d axis where we shall denote actually P as a form of the differentiation, it is common notations and I for the specific converter, it can be, you have n number of converters.

So, i can be 1, 2, 3, 4 to m. So, this is all about it and dynamic equation of the transmission line between the 2 converter is given by, so it is a Vmiq and minus Vmij, this is ith and the jth element, so it is R12 x ijq, so on. Similarly, it will follow through the d frame with just nomenclature will change and there will be a cost component here that is physically it will be d and this component will be q and cross component will be with the omega.

(Refer Slide Time: 07:13)

Mathematical Analysis of Microgrid Structure (cont...)

- A composite load has been assumed to be present as electrical load on microgrid, which consists of a linear, a nonlinear, and a constant power-type loads. The dynamics of these loads are presented as follows:
  - Linear load equations

$$V_{miq} = R_{Li} I_{Liq} + L_{Li} p I_{Liq} + \omega_{si} L_{Li} I_{Lid} \quad (5)$$

$$V_{mid} = R_{Li} I_{Lid} + L_{Li} p I_{Lid} - \omega_{si} L_{Li} I_{Liq} \quad (6)$$

  - Nonlinear load equation

$$I_{nonq} = \frac{2}{3} \frac{P_{inon} V_{miq} - Q_{inon} V_{mid}}{V_{mid}^2 + V_{miq}^2} \quad (7)$$

$$I_{nond} = \frac{2}{3} \frac{P_{inon} V_{mid} + Q_{inon} V_{miq}}{V_{mid}^2 + V_{miq}^2} \quad (8)$$

A composite load has been assumed to be present as electrical load on the microgrid, which consists of linear, nonlinear, constant power-type loads. The dynamics of this loads are represented as follows. So Vmiq = LiLiq + Lq and with the term of the cross link that is omega Li x id. Similarly, you will have this term's cross link.

So, nonlinear load equations, we can write it that nonlinear Iq will be 2/3 Pinonmiq x -, I say it is specifically to be P x V – Q x V/V square plus Vd square + Vq square. Similarly, for the d-axis, all the nomenclature will be changed to d, but this one will be mind it, it will be a q and for q it will be d and for d this term will be q.

(Refer Slide Time: 08:36)

Mathematical Analysis of Microgrid Structure (cont...)

- Constant power-type load equations

$$I_{iq} = \frac{2}{3} \frac{P_i V_{miq} - Q_i V_{mid}}{V_{mid}^2 + V_{miq}^2} \quad (9)$$

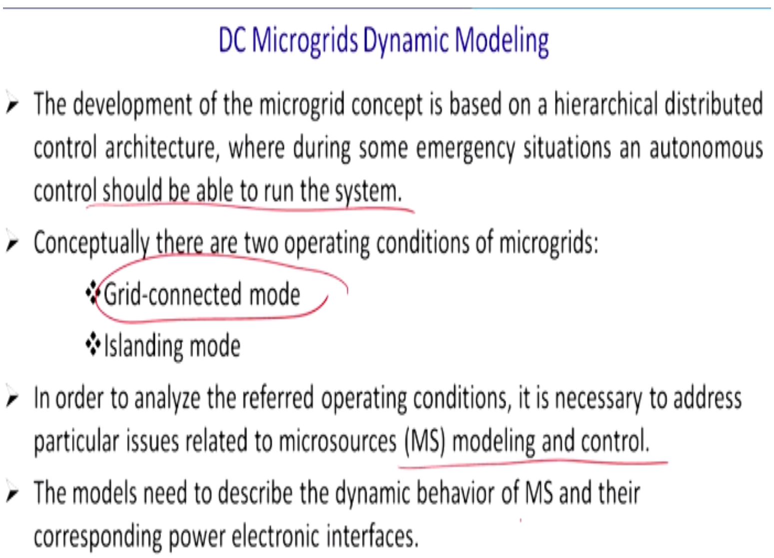
$$I_{id} = \frac{2}{3} \frac{P_i V_{mid} + Q_i V_{miq}}{V_{mid}^2 + V_{miq}^2} \quad (10)$$

- On the basis of the dynamic model of a parallel converter microgrid system, both transient and steady-state operation analyses can be performed.
- However, a microgrid operating in autonomous mode will only operate when voltage and frequency stabilization condition is met. Thus, a proper control techniques should employed.

So, for the constant power-type sources, we have to model different kind of. So ultimately what you understand constant power-type sources, if voltage drops, then it will drank more current. So, this kind of sources, it will change little bit. Ultimately, you know it is 2/3 Pimiiq – Qimid and similarly, it will be for the q-axis. On the basis of the dynamic model of the parallel converter in the microgrid system, both transient and the steady state operation can be analyzed and performed.

So, however the microgrid operating in an autonomous mode will operate when voltage and frequency stabilization conditions is met. So, we have to see that once it is connected in aligning mode, you can have own frequencies and once you are connected to the grid, so you should have the frequency and voltage at the stabilization condition, means that otherwise it will be restricted at the distribution of the disturbance of the sources.

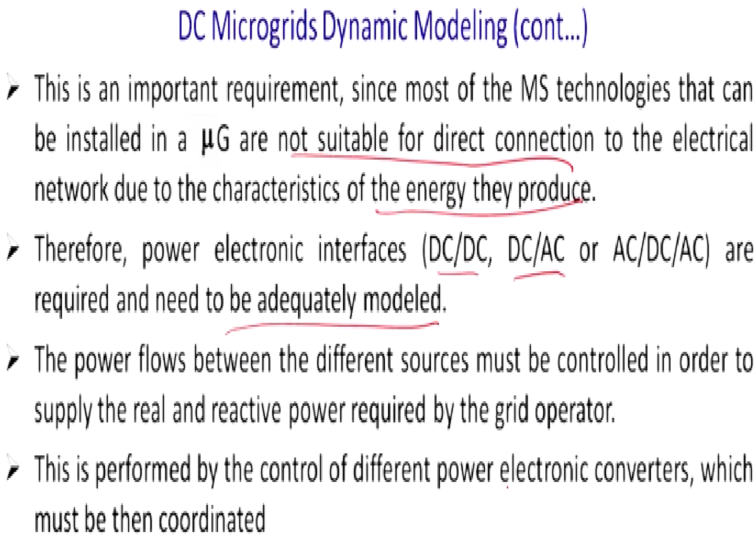
(Refer Slide Time: 10:08)



The development of the microgrid concept is based on the hierarchical distributed control architecture where during the emergency situation, an autonomous control should be able to run the system, you put in into auto mode. Conceptually, to the 2 mode, there are 2 operating conditions, one is grid-connected mode that will govern, another is the islanding mode.

In order to analyze the different analyze the different operating conditions, it is necessary to address the particular issues related to the microsources and modeling of the modeling and the controllers. The models need to describe the dynamic behavior of microsources and their corresponding power electronics interface.

(Refer Slide Time: 10:53)



This is an important requirement because since most of the microsources microtechnologies that can be installed in the microgrid are not suitable for the direct connection to the electrical network due to its characteristics of the energy they produce. We cannot directly integrate DC to DC your solar inverter, sorry, your wind turbine into the grid. So, you require to have a, you require to have gearboxes DFIG, thereafter you have a rotor site converter that will maintain the slip power.

So, therefore, power electronics interfaces DC to DC, DC to AC, AC-DC AC/DC/AC are require to need to be accurately modeled. The power flow between the different sources must be controlled in order to supply that real active power required by the grid power. This performance of the control of different power electronics converter, and which required to be coordinated among themselves.

(Refer Slide Time: 12:11)

Microsources Dynamics in DC Grid

- Consider a dc microgrid with PV source, energy storage system and the grid supply.
- In order to design the control system of the PV source, the model of the entire system has to be analyzed.
- For the modeling of the PV-based active generator, all the modulated values can be replaced by their average values during the modulation period.
- The equivalent electrical diagram with the equivalent average modeling of power electronic converters consisting of the PV system, the ESS, the grid connection, and the DC bus is illustrated in Fig.2.

So, consider a DC microgrid with a PV source, energy storage system and the grid supply. In our to design the control system of the PV source, the model of the entire system has to be analyzed. For the modeling of the PV-based active generator, all the modulated values can be replaced by their average values during the modulation period. The equivalent electrical diagram with the equivalent average modeling of the power electronic converters since you have, there are 2 states by switching on and switching off.

So, average model required to be considered. Consisting of the PV system, the energy storage system, the grid connection and the DC bus is illustrating the next figure. You see that this one.

(Refer Slide Time: 13:06)

DC Microgrid Source Dynamics (cont...)

- The three power converters are used to introduce control inputs for each power conversion system, in order to control the power generated by the PV panels, to maintain a constant DC-bus voltage, to supply the required power exchange with the grid, and to ensure the power buffering of each energy storage unit.

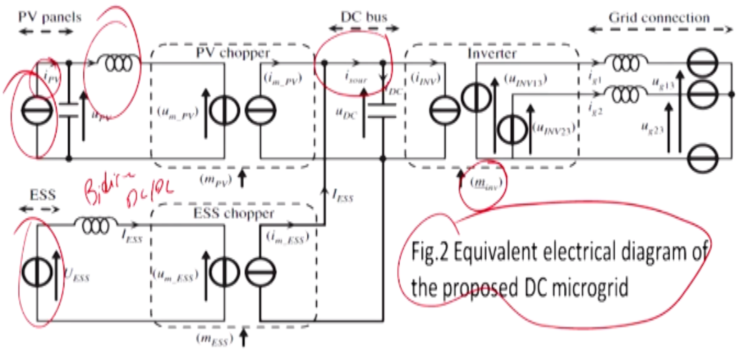
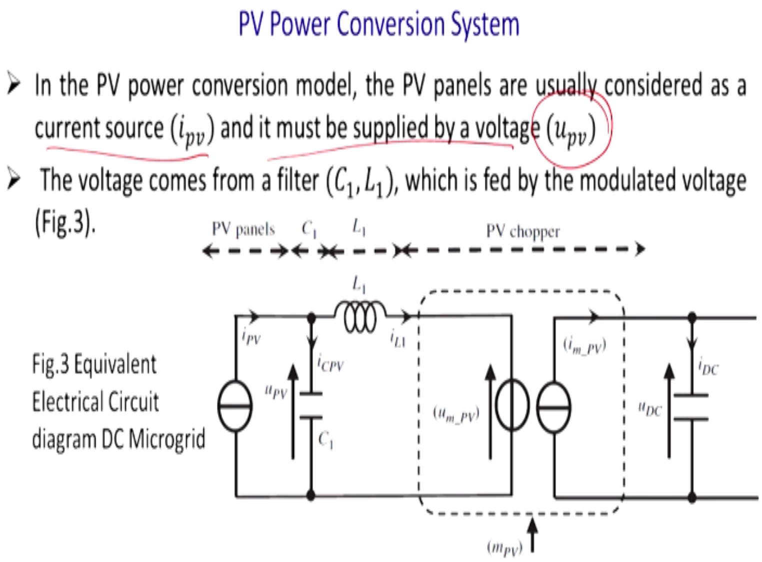


Fig.2 Equivalent electrical diagram of the proposed DC microgrid

This is we will model it as a current source. Thereafter, you got an inductor and ultimately you got PV chopper and this will be a current control voltage source. So, you got to a DC bus and thereafter you got an inverter and you are feeding the power to it. On panel you may have we are maintaining a DC bus and you are charging the capacitor. So, you can have the whole system in place.

So, let us analyse it. The 3 power converters are used to introduce that control input on the each for conversion in order to control the power generated by the PV panels, to maintain constant DC bus voltage to supply required power exchange with the grid and to ensure the power buffering up each storage unit. So, this is something we require to control these things and thus, we have this, all these 3 converted topologies.

(Refer Slide Time: 14:24)



So, now, let us take PV power conversion system. The PV power conversion model, the PV panels are usually considered as a current source. We have we have discussed about the modeling of PV cell, it is just it will be now represented by the connection only and it must be supplied by the voltage Upv and the voltage comes from the filter that is basically C1, L1 which is fed to the modulated voltage of figure 3.

So, this becomes the your PV power conversion system of the model, equivalent circuit diagram of the of the DC microgrid for PV power conversion.

(Refer Slide Time: 15:09)

PV Power Conversion System (cont...)

- The inductor is also modeled as a current source i_{L1}. This current depends on the PV voltage and the modulated voltage of the chopper output (u_{m_pv}):

$$L_1 \frac{di_{L1}}{dt} = u_{m_{pv}}(t) - u_{pv}(t) \qquad (11)$$

- Losses in the filter and the capacitor are neglected. The capacitor (C_1)can stabilize the voltage (u_{pv}) across the terminals of the PV panels.
- This capacitor can be modeled by using the PV current (i_{pv}) and the filtered current i_{L1}:

$$\begin{cases} \frac{du_{pv}}{dt} = \frac{1}{C_1} i_{CPV}(t) \\ i_{CPV}(t) = i_{PV}(t) - i_{L1}(t) \end{cases} \qquad (12)$$

So, let us write differential equations on the expressed model of it. The inductor is also modeled as a current source L1. The current depends on the PV voltage and the modulated voltage of the chopper output, that is Umpv. So, thus L1 Ldi/dt = Umpvt – Upv. Lossses in the filters and the capacitors are neglected. The capacitor C1 can stabilize the pv across the terminal of the panels. The capacitor can be modeled by using the PV current and filtered current iL1. So dupv/dt = 1/C iCPV, so iCPVt = ipV – iL1.

(Refer Slide Time: 16:07)

PV Power Conversion System (cont...)

- i_{CPV} is the injected current in capacitor. The mean value of the terminal voltage of the chopper (u_{m_pv}) is obtained from the DC voltage (u_{DC}) and the duty cycle ratio ($m_{\_pv}$):

$$\langle u_{m\_PV} \rangle = m_{PV} * u_{DC}(t) \qquad (13)$$

$$\langle i_{m\_PV} \rangle = m_{PV} - i_{L1}(t)$$

Energy Storage System (ESS)

- In the models of ESSs, an ESS is usually considered as a voltage source (u_{ESS}), which is connected to a choke filter (L_2) (see Fig.4)

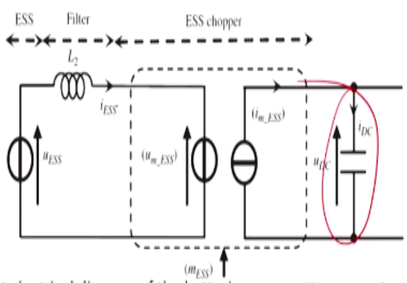
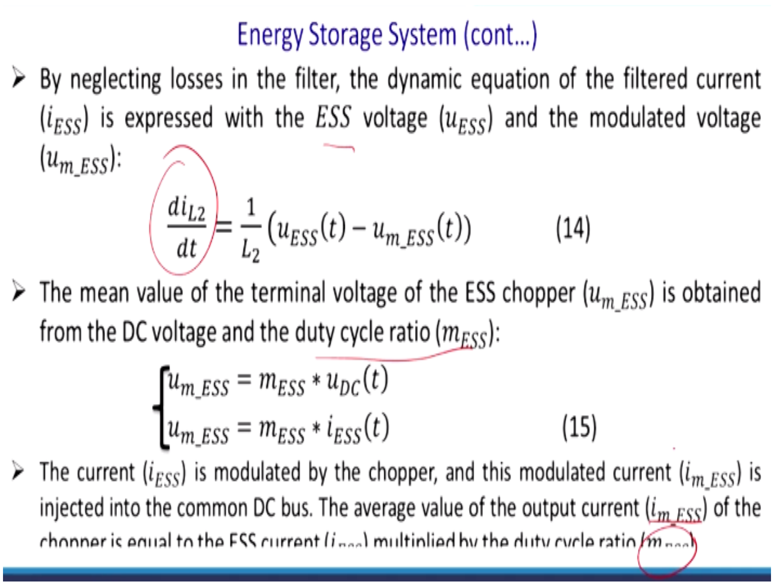


Fig.4 Equivalent electrical diagram of the batteries energy storage system

iCPV is the injected current in the capacitor. The mean value of the terminal voltage of the chopper is operand from the DC voltage and that duty cycle ratios. So, UmPV = mPV x uDC; imPV = mPV – iL1t. So, you got an energy storage system in the model of ESS, and ESS is considered as a voltage source that is an electrical storage element and the voltage is Uss which is connected with the choke of the filter, it may be ultracapacitor, it may be the battery, which connected to the choke of the filter that is L2. So, ultimately this is the ESS and you got uDC here.

(Refer Slide Time: 17:14)



So similarly, by neglecting the losses of the filters, the dynamic equations of the filter current iESS expressed with the ESS voltage uESS and modulated voltage. So, dL/dt = 1/L2 uESSt – umSSt. The mean value of the terminal voltage of the of the ESS chopper is umESS obtained from the DC voltage and the duty cycle ration mESS. So umSS = mESS x uDC and mESS = mESS x iESS.

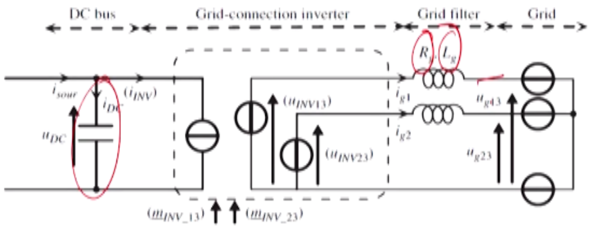
The current it iESS is modulated by the chopper and this modulated current iMESS is injected to the common DC bus and the voltage value of the output voltage is iMESS and the chopper current is equal to the iSS current and is multiplied by the duty cycle ratio of mESS.

(Refer Slide Time: 18:22)

Grid Connection

- A three-phase inverter within a choke as filter is used for the grid connection.
- An equivalent mean modeling of this three-phase inverter is sufficient for representing fundamental components of voltage/current (Fig.5) as dependent phase-to-phase voltage sources (u_{INV_13} and u_{INV_23}) with the DC-bus voltage (u_{DC}) via modulation indexes ($m_{INV_13}$and m_{INV_23}) and a dependent current source (i_{INV}) with AC currents through the same modulation indexes.

Fig.5 Electrical diagram of the grid connection



The three-phase inverter within a choke as a filter is used for the grid connections. An equivalent mean modeling of the three-phase inventor is sufficient to represent the fundamental component of voltage current of figure 5 as dependent on phase-to-phase voltage source, that is, uINV of 13 and uINV of 23 within the DC bus voltage uDC via modulated indexes mIV_13 and miNV_23 and a dependent current sources iNV will be with AC current through the same modulation index.

So you got an electrical diagram of the grid connections. So, you got iDC and thus you have 2 controllers, that is RGLG and it is fed into the grid.

(Refer Slide Time: 19:20)

Grid Connection (cont...)

- Then mean values of modulated phase-to-phase voltages and of the average currents are expressed as:

$$u_{INV\_13} = m_{INV\_13} * u_{DC}$$

$$u_{INV\_23} = m_{INV\_23} * u_{DC} \quad (16)$$

$$i_{m\_PV} = m_{INV\_13} * i_{g1} + m_{INV\_23} * i_{g2} \quad (17)$$

- By assuming that grid voltages are balanced, line voltages are obtained through:

$$\begin{cases} u_{INV1} = \frac{2}{3}u_{INV\_13} - \frac{1}{3}u_{INV\_23} \\ u_{INV2} = -\frac{1}{3}u_{INV\_13} + \frac{2}{3}u_{INV\_23} \end{cases} \quad (18)$$

The mean value of modulated phase-to-phase voltage of the average current is expressed as uINV-13 = mINV_13 x uDC; uINV_23 = this modulation index into uDC and thus the imPV

= this actually INV_13 x ig1 that is the gate current of it and INV_13 x ig2. Assuming that grid voltages are balanced, so you have a more complexity when your grid voltage is unbalanced, the line voltage can be obtained by uINV1 = 2/3 uINV_13 – 2/3 uINV_23; uINV = -1/3uINV_13 + 2/3 uINV_23.

(Refer Slide Time: 20:20)

Grid Connection (cont...)

- The filter currents are deduced from the following differential equations:

$$\begin{cases} \frac{di_{g1}}{dt} = \frac{1}{L_g}(v_{INV1} - R_g * i_{g1} - v_{g1}) \\ \frac{di_{g2}}{dt} = \frac{1}{L_g}(v_{INV2} - R_g * i_{g2} - v_{g2}) \end{cases} \quad (19)$$

- Three-phase inverter voltages, grid voltages, currents, and duty cycles can be expressed as vectors, respectively, by:

$$v_{INV} = \begin{bmatrix} v_{INV1} \\ v_{INV2} \\ v_{INV3} \end{bmatrix}, v_g = \begin{bmatrix} v_{g1} \\ v_{g2} \\ v_{g3} \end{bmatrix}, i_g = \begin{bmatrix} i_{g1} \\ i_{g2} \\ i_{g3} \end{bmatrix}, m_{INV} = \begin{bmatrix} m_{INV\_13} \\ m_{INV\_23} \end{bmatrix} \quad (20)$$

The filter currents are deduced from the following questions. So, it is ig1t = 1/Lg that is the grid inductor iv inverter 1 – Rg x ig – the grid voltage 1. Similarly, you can have ig2dt = 1/Lg inverter 2 Rg x ig x vg2. So the three-phase inverter voltages, grid voltages, current, and duty cycle can be expressed into the vector form. These are the 3 voltages of the 3 inverters. So, these are the grid voltages and that should be equal and these are grid currents and these are the modulation index of this grid inverter.

(Refer Slide Time: 21:23)

The DC Bus Dynamic Equation

- In this hybrid generating system, three energy sources (PV panels, ESS, and the electrical grid) are all connected to the common DC bus via different power electronic converters as shown in Fig.2.
- So according to this DC-coupling, the capacitor current of the DC bus (i_{DC}) is expressed as:

$$i_{sour}(t) = i_{m\_ESS}(t) + i_{m\_PV}(t) \quad (21)$$

$$i_{DC}(t) = i_{sour}(t) - i_{INV}(t) \quad (22)$$

- where i_{m_PV} is the modulated current from the PV chopper, i_{m_ESS} is the modulated current from the ESS chopper, and i_{INV} is the modulated current from the grid inverter.

In this hybrid generating system, 3 energy sources; PV panel, ESS and electrical grids are connected to the common DC bus via different power electronics converter. We have seen this thing in the figure number 2, please recall that. So, according to the DC-coupling, the capacitor current iDC is expressed as is = im_ESS + im_PV. So iDC = I of source – i of inverter, where im_PV is the modulated current from the PV chopper and im_ESS is the modulated current from the energy storage chopper, and iINV is the modulated current from the grid converter.

(Refer Slide Time: 22:22)

The DC Bus Dynamic Equation (cont...)

- DC-bus voltage is expressed as:

$$\frac{du_{DC}}{dt} = \frac{1}{C_{DC}} i_{DC}(t) \qquad (23)$$

- Where C_{DC} is the capacitor of the DC bus

So, thus we can express this DC bus current as your uDCt = 1/Cdt of t where CDC is the capacitor voltage of the DC bus. You know, we wanted to show something like to go back in this figure 5 and you see that so this is the DC site of it this is the 2 inverters or it can be taken as a one phase of the inverter also. Inverter is connected, that is inverter 1, 3 that is generating the voltage and this thing is the grid side inductor, generally it has been placed inside the so, inside the solar inverter only, and of course, it will come with some amount of the resistance.

It is don't, please not misunderstand that assume it is a source inductance of the grid, it is generally physically connected into the system, thus this value is known to you, similarly for this other values, and considering that you can actually inject current into the system. So, you can have 3 element here, 2 elements are essentially voltage and the current. So, here it is a source and source is essentially consists of maybe the ESS and iM_PV and the DC part of it that is coming from the source that is the DC source and the minus inverter.

So, this is the combination of it, and let us go back again, you know overall control circuitry, so that we can recall our system better. So, this is the figure number 2. So, now, it is iPV and this thing is uPV and ultimately this is your PV chopper part and here you got an inverter and where actually your modulation index comes into the picture, and from this modulation index, you have this inverter connected to a system and you are injecting the power into the system, and thereafter this thing is your energy storing element and this thing essentially a bidirectional DC to DC converter.

So, it will be going through this. When you have a surplus power, it will store mostly the battery and it will take out the power once there is a there is a pro there is actually energy deficiency into the local grid and most of the this model is essentially generally coupled with the local resistances or the local load, then only analyse will be accomplished, sometime we will provide resist provide a load here before the connections to the grid, so that it can also operate in the islanding mode.

Thank you for your attention. We shall continue to our discussions with DC Microgrid in our next classes.