Introduction to Smart Grid
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Lecture – 27
Operation and Control of DC Microgrid- I

Welcome you all for today's lecture on Operation and Control of DC Microgrid. As we all know currently the whole world is looking forward towards low carbon footprints, indirectly maximum renewable presence in any power system will be of high importance and to achieve those goals especially country like India where maximum solar penetration expected in next 5 to 10 years.

And as per the government policy we looking forward to as maximum and as high as 100 gigawatt of solar presence in near future within 1 decade. Though it is a new challenge, but the concept of DC microgrid looks very potential in the presence of renewable energy where the generation especially the PV which is coming from in the form of DC and the most of the important loads are also of DC in nature.

So, to maintain the balance between supply and the load and when maximum generation are from DC as well as maximum loads are from DC it is not a bad idea to plan for a mini DC grid to represent DC smart grid or DC microgrid. Especially in case of island mode operations for rural hilly areas it could be a viable option to go from AC microgrid to DC micro grid. But being said that DC microgrid implementation become very big challenge compared to AC microgrid because, there is no frequency presence in the whole grid due to the absence of frequency. It is also difficult for us to implement the existing power frequency droop characteristics which is very popular in case of us system cannot be directly embedded into my DC grid.

So, we have to think for more innovations for PV droop characteristics for control mechanism. So, when we have a DC microgrid in place connected to my grid which is AC in nature; So, now the balance between DC microgrid and AC grid which is very large in nature to be maintained by exchanging energy from DC microgrid to AC grid and from AC grid to DC microgrid. During the energy exchange of I mean it is quite challenging because most of the time the PV and wind generator is connected to my DC microgrid do try to operated mppt mode. So, that the maximum energy can be extracted from the DC grid scattered to it is local load and the excess energy can penetrate to my AC grid.

Similarly when the load of the DC microgrid is more we can extract power from the AC grid to meet that DC load, but that case become heavily complicated when it is islanded mode of operation whether DC microgrid has to balance it is energy locally without any grid support. Under those circumstances we need to have a storage mechanism as and when there is excess energy available to me the storage can be charged or the battery can be discharge and when the load is more compared to my generation the battery can discharge.

So, we will two different kind of operations, but the DC microgrid connected to AC grid or when it is operating with it is isolated mode, but to achieve all those without the presence of frequency and the control mechanism become very very challenging. The one important concept here that I liked to highlight now because we have so many cables around in the case of DC microgrid the voltage the setting of voltage level for the DC microgrid become an issue. It is good that you operate very low voltage of DC, but when you reduce the voltage the current is quite high and the cable size become keep on increasing the thickness of the cable is too high.

So, preferably we like to operate it at 48 volt DC could be 96 could be order 300 and 600 volt DC, but for residential area or may be for any commercial, it would be good to have operation between 48 volt to 96 volts. It is ongoing research in space and with couple of years from now you will have a clear picture about the standardization of DC grid.

So, that all the voltage level can be identified and the devices those will be connected to my DC grid will also follow the standards specified for DC microgrid operation. So, with this introduction let us get into the operation and control challenges of DC microgrid. Now one of the major issue today is the controlling of all the generation presents within a DC microgrid. Now, there are three major control mechanisms one is decentralized control, distributed control, and centralized control and all this controls depending upon the scenarios we need to adapt one of those three so, that a better control mechanism can be incorporated for successful operation of DC micro grid.

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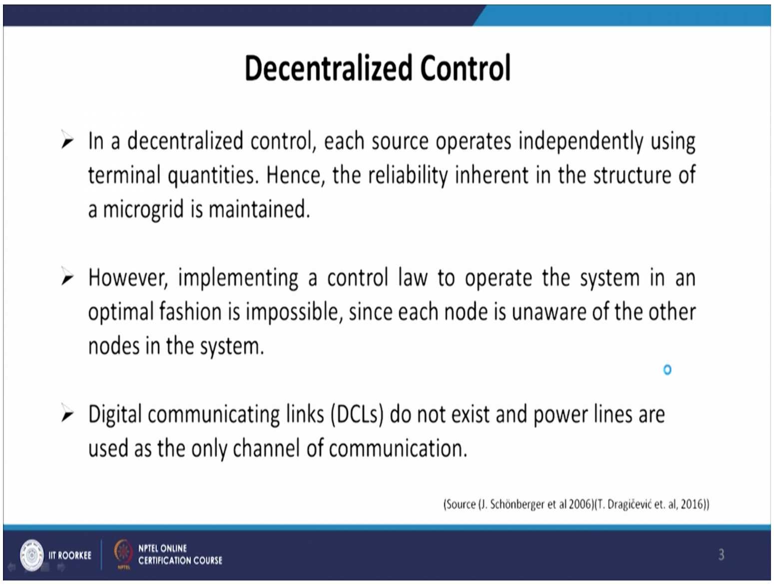

Now, let us begin with decentralized control, in a decentralized control each source operate independently using terminal quantities hence the reliability inherent in the structure of a microgrid is maintained. However, implementing a controller to operate the system in an optimal fashion is impossible, since each node is unaware of the other nodes in the system very merit of decentralized control that it is very robust and the reliable, but the problem here no one generator not be able to understand that control mechanism operation strategy of other generator.

So, there is no communication place so, during decentralized control it is reliable, very improved concept, but that there are few challenges because the generators do not speak to each other or talk to each other. Digital communication links DCLs do not exist and power lines are used as a only channel of communications. Now in case of centralized control each source is controlled from a single using a central controller and communication link.

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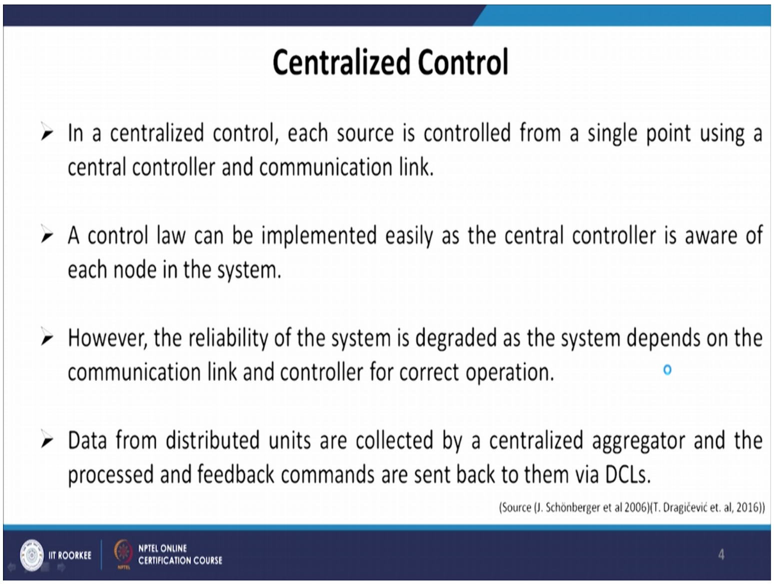

So, centralized control is very very popular, but a control law can be implemented easily is the central controller is aware of each node in the system means the central controller understand what is happening at the PV bus, what is happening at wind generator connected bus, what is happening my battery storage connected bus.

So, the centralized control seems to be a smarter one; however, the reliability of the system is degraded as the system depends on the communication link and due to any reason if the communication fails then the centralized control approach may not be may not be work well during failure of communication link. Data from distributed units are collected by a centralized aggregator and the processed and feedback commands are sent back via DCLs.

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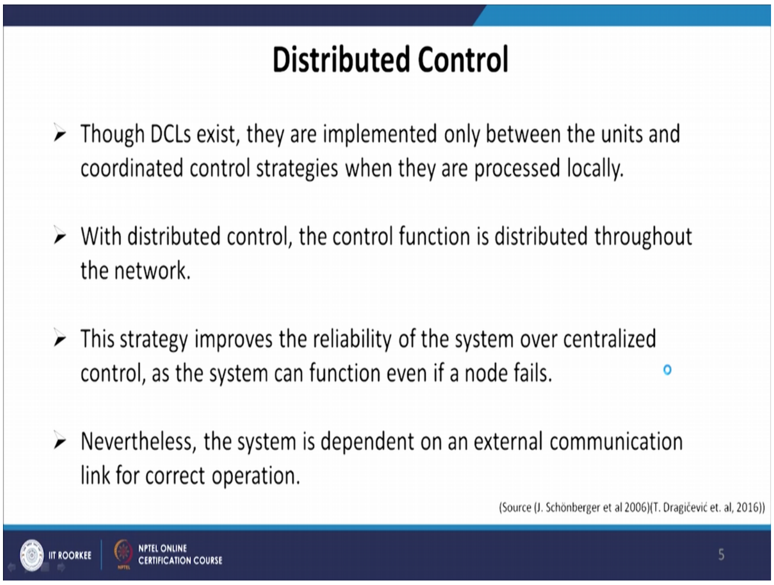

Now, in case of distributed control though DCLs exist they are implemented only between the units and coordinate control strategies when they are processed locally, with distributed control the control function is distributed throughout the network. This strategy improves the reliability of the system over centralized control as the system can function even a node fails in case of distributed control even at a given point if a generation is disconnected of the node fails still the control mechanism do follow it is functions without fail.

Nevertheless, the system is dependent on an external communication link for correct operation distribution control distributed controlled is very important very advantages smart, but we need to have an excellent communicate link to achieve it is goal. Now there are different type of decentralized control.

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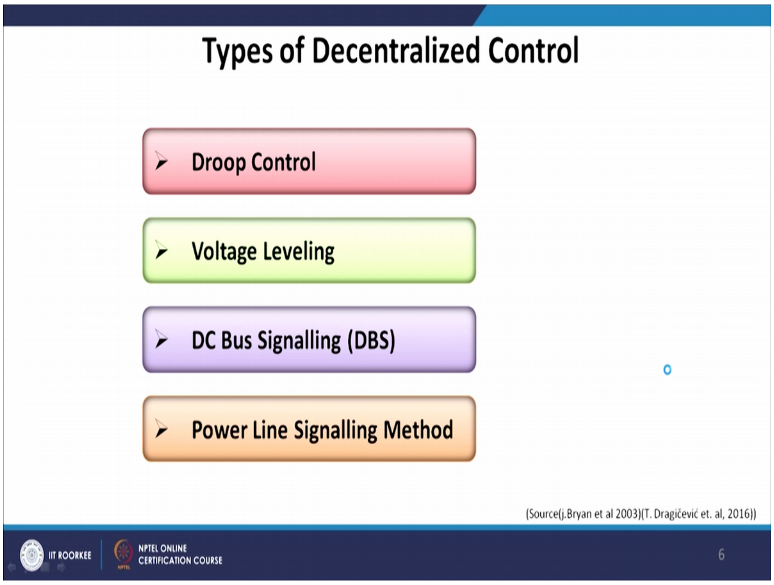

Let us slowly see because we talked about a decentralized control, centralized control, distributed control and then will now try to see what are the schemes available under the heading of the decentralized control; One of the very commonly established decentralized control is my droop control, voltage level control, DC bus signaling, and power line signaling method.

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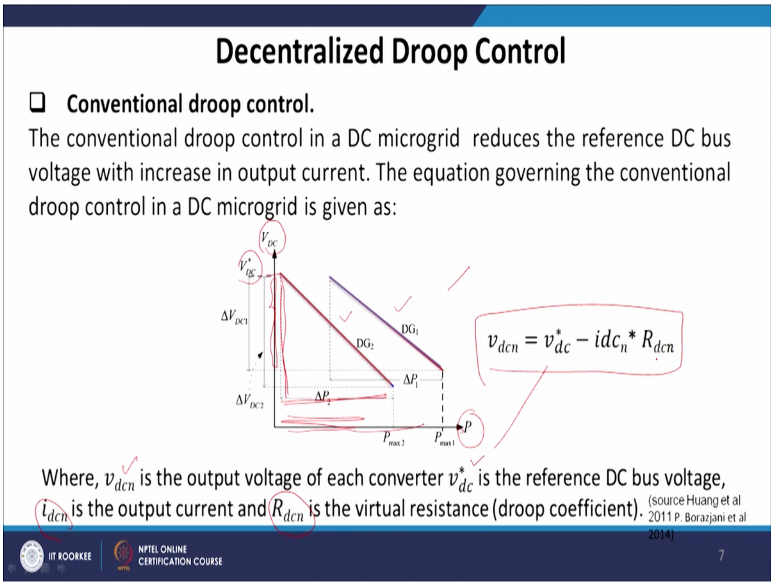

Now, in case of droop control we all ever in case of a droop if it could be my I mean power versus frequency for queue versus voltage or in case of DC it is voltage versus, now when we drop the voltage certainly the power is going to vary. But depending upon the slope the magnitude of power variation depends or vice versa when power varies the voltage has to vary and depending upon the slope the magnitude will be decided.

Now, in case of a conventional droop control, the conventional droop control in DC microgrid reduces the reference DC bus voltage with increase in output current. The equation governing the conventional droop control in a DC microgrid is given by. Now if you consider the droop control P versus V DC as I have mentioned earlier in the past we used to plot this characteristic where we had P and f for AC networks, but due the absence of frequency now we are plotting the graph drop droop characteristics for V versus P.

Now this the droop characteristic for my DC, DC 1 and DC 2, DC 1 and two different DCs and you could see if there is a voltage drop certainly there is a power change or power change leads to a voltage variation. Now if I do see, now the V DC star is the operational voltage and that keep on varying with respect to change in my power, one thing is very clear when the load is more if the load current is more the power extracted from the system is more than certainly there is a drop in voltage.

So, if the load current is high and I can certainly conclude that the voltage is going to drop now this is basically with respect to my converter, where v dn is the output voltage of each converter and v dc star which is the reference DC voltage and idc n is the output current and R dcn is a virtual resistance are the droop coefficient.

Now what is the major drawback in droop control, the major drawback is that if the slope is different than your voltage regulation will keep on varying with different slope you will have different voltage regulation and that may lead to good voltage regulation or bad voltage regulation. Similarly when you like to share a load and that load sharing may be before depending upon the slope of the droop and sometime it is excellent depending upon the slope of the droop.

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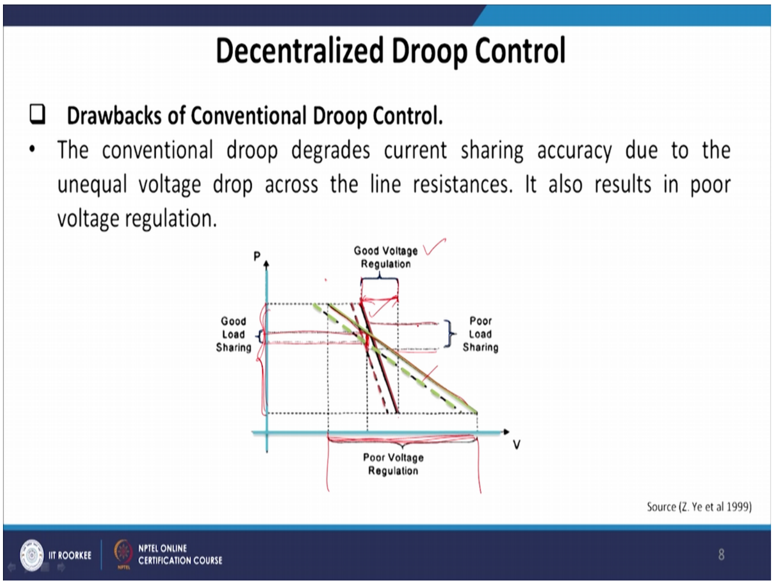

So, conventional droop degrades current sharing accuracy due to the unequal voltage drop across the line resistances it also results in poor voltage regulation. Now let us focus in the previous diagram V versus P, now it is P versus V for a given droop characteristic. Now you can see this is what the voltage variation, it can experience for a power drop between this range.

So, if there is a power drop you could see there is a huge voltage drop and hence it is of poor voltage regulation, but the same power drop for this characteristic you could see the voltage drop is of this range and compared to this voltage drop you can see the voltage drop is reasonably smaller. And I can say for this red characteristic it has good voltage regulation where is for the green characters take it is a poor voltage regulation for the equal amount of power variation.

Similarly, we can see that the given if there is a variation in the droop characteristic we could see that is a good load sharing in case of the green one and where is poor 4 load sharing in case of the red one. So, few in indirectly I can say that if you achieve good voltage regulation you will have actually poor load sharing and if you have good load sharing then you will experience poor voltage regulation. So, that is what one of the very common challenge we do face in case of conventional droop control concepts.

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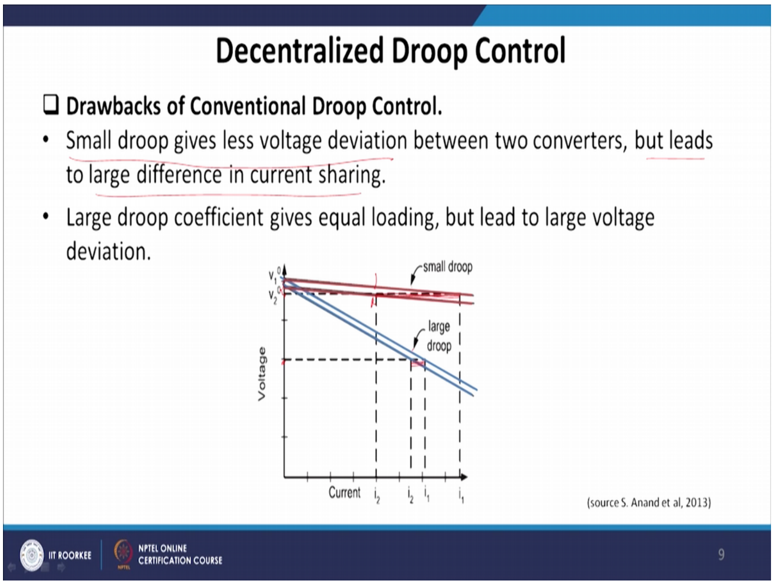

Now, in case of decentralized droop control few further drawbacks that we need to highlight here small droop less voltage deviation between two converters, but less to large difference in current sharing. So, what it wants to say that, when there is a small droop gives less voltage deviation I mean if there is a small droop it is a less voltage deviation, but it leads to large difference in current sharing, but it leads to large current sharing.

If there is a small variation depending upon the characteristic you could see there is a huge current variation and here it is a less current variation. So, small droop leads to large cur current de deviation large droop small current variation for a given voltage of operation. So, large droop coefficient give equal loading, but lead to large voltage deviation to.

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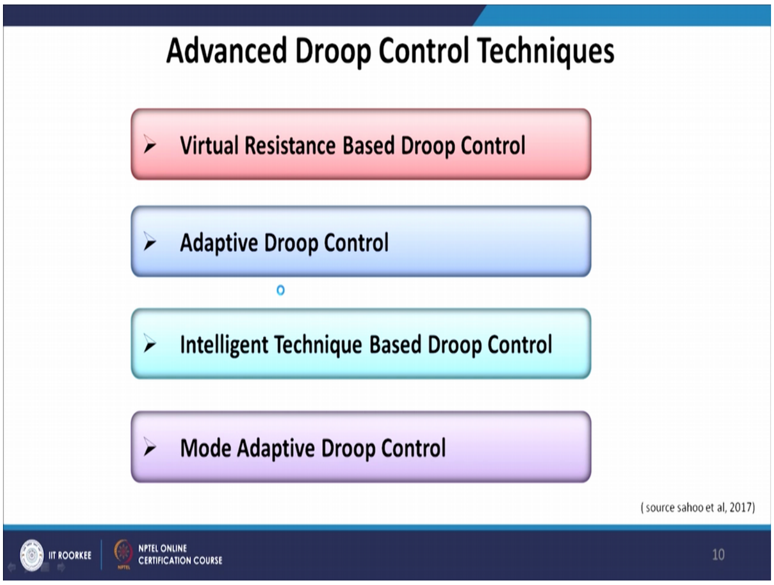

Now, there are few advanced droop control techniques which are in place virtual resistance based droop control, adaptive droop control, intelligent technique based droop control, mode adaptive droop control.

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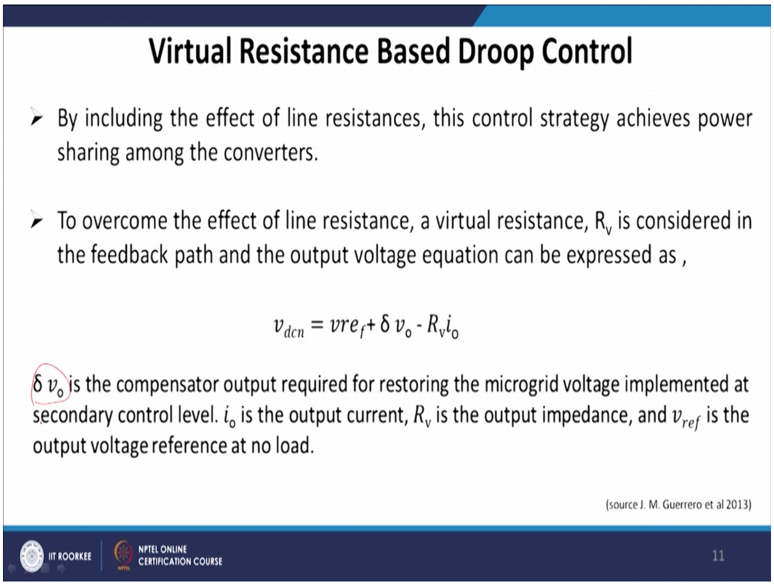

So, virtual resistance based droop control by including the effect of the line resistance as I mentioned earlier that during any control mechanism in case of a DC Microgrid in specific where the line drops. For example, we have 2 generators and connected to 2 different cables, now the if you generate P kilowatt of power and when it is retest reaches to another node it is P minus the drop is available to me and the current flowing in each and every cable is not known to me easily. And hence predicting the generation mix to meet the load considering the load resistance of the cable and the line drops become a challenge.

So, by including the effect of line resistances this control strategy achieves power sharing among the converters. To overcome the effect of line resistance, a virtual resistance, R v is considered in the feedback path and the output voltage equation can be expressed as V dcn equal to vre f plus delta v naught minus R v i, where delete v naught is the compensator output required for storing the microwave voltage implemented at secondary control level of as well as I naught is the output current and R v is the output impedance and v reference is the output voltage reference at no load.

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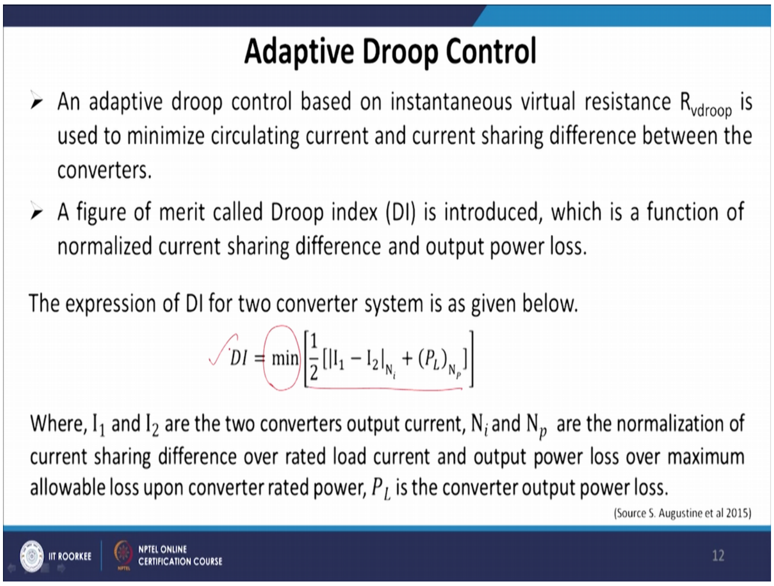

Now, adaptive droop control, an adaptive droop control based on instantaneous virtual resistance R v droop is used to maxi minimize circulating current and current sharing difference between the converters. A figure of merit called droop index very important DI is introduced which is a function of normalized current sharing difference and output power loss.

The expression for droop index for 2 converter system is given by half of is given by half of I 1 minus I 2 plus P L. And that is expected we have to minimize this function to achieve the DI, where I 1 and I 2 are the 2 output currents of the converters N i and N p are the normalization of current sharing difference overrated load current and output power loss over maximum allowable upon converter rated power where as P L is the converter output power loss.

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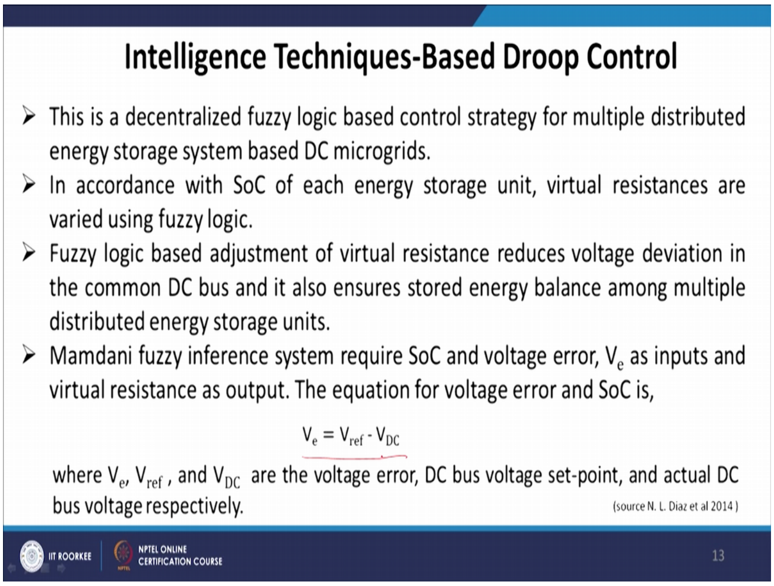

Now, few intelligent technique based droop control over a period of time like last one decade intelligent technique became very popular. So, literature justifies that there are few intelligent technique based droop control which are in place. This is a decentralized fuzzy logic based control strategy for multiple distributed energy storage system based DC microgrid.

In accordance with SoC state of charge of each energy storage unit, virtual resistance are varied using fuzzy logic because no one knows what exactly the virtual resistance is. So, that is varied for an optimal operation. So, fuzzy logic based adjustment of virtual resistance reduces voltage deviation in the common DC bus and it also ensures stored energy balance among multiple distributed energy storage units.

Mamdani fuzzy interference system require SoC and voltage error V e as inputs an virtual resistance as output means by giving the SoC and voltage error we can calculate the virtual resistance. The equation for voltage error and SoC is given by V e equal to V ref minus V DC, where V e V ref V DC are the voltage error DC bus voltage set point and actual DC bus voltage respectively.

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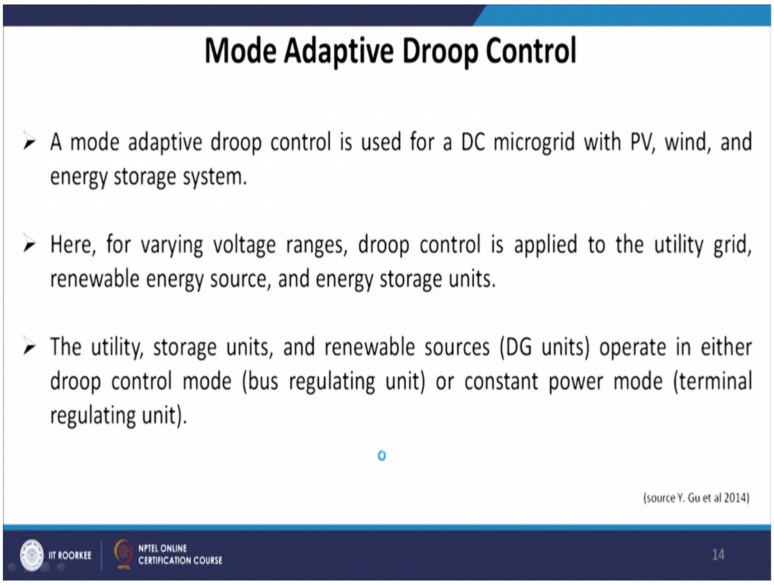

A mode adaptive droop control, a mode adaptive droop control is used for a DC microgrid with PV, wind and energy storage system interesting. So, now, here for varying voltage range droop control is applied to the utility grid renewable energy sources and energy storage units. The utility storage units and renewable energy sources operate in either the droop control mode or at a constant power mode.

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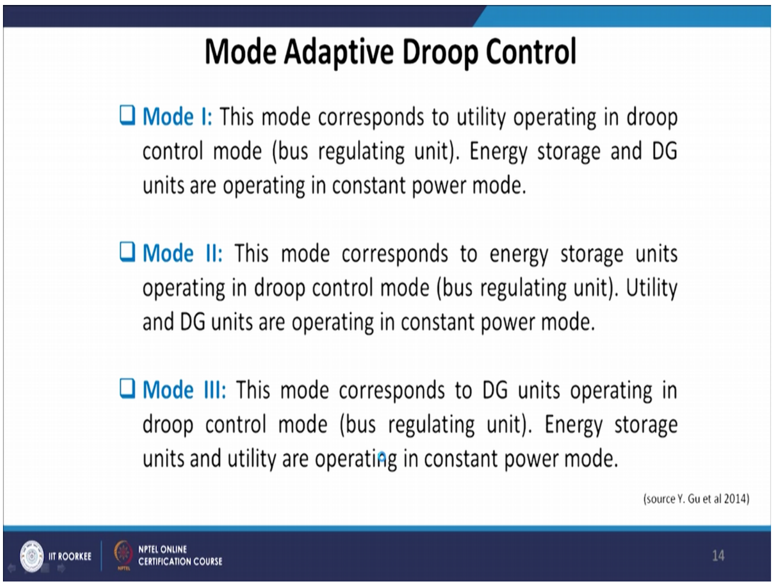

Now, we will consider actually 3 different mode of operation where we have seen will be talking about utility grid renewal energy sources and the energy storage. So, my utility grid is one of the source for me I can take energy as it can source for me and very rarely it can be sync, but most probably it source for me and the energy storage is again storage device within my DC grid and the renewable energy source within my DC grid can act as a storage.

So, we have 3 sources the utility grid itself as a energy source battery or storage mechanism renewables like PV also my storage. So, there are 3 source of energy storage PV and utility grid and we need to operate all the 3 of them in a different pattern. Now the mode one the first way of operation this mode corresponds to utility operating in droop control mode energy storage and DC are operating in constant power mode ok. The utility is in droop control mode where as the storage and DC operating constant power mode where as in mode 2 where the energy storage operate in droop control mode where as utility and DC act as a constant power mode.

Mode 3 where actually we allow the DC to operate in control droop control mode and the energy storage and utility can operate in the constant power mode, if you say it is ABC, A if one of them is at control mode droop control mode A is in droop control mode. So, B and C are operated constant power mode and similarly alternatively B is your droop control mode, A and C are in constant power mode and C is in the droop control mode, A and B are in the constant power mode.

Now let us move into voltage level signaling approach.

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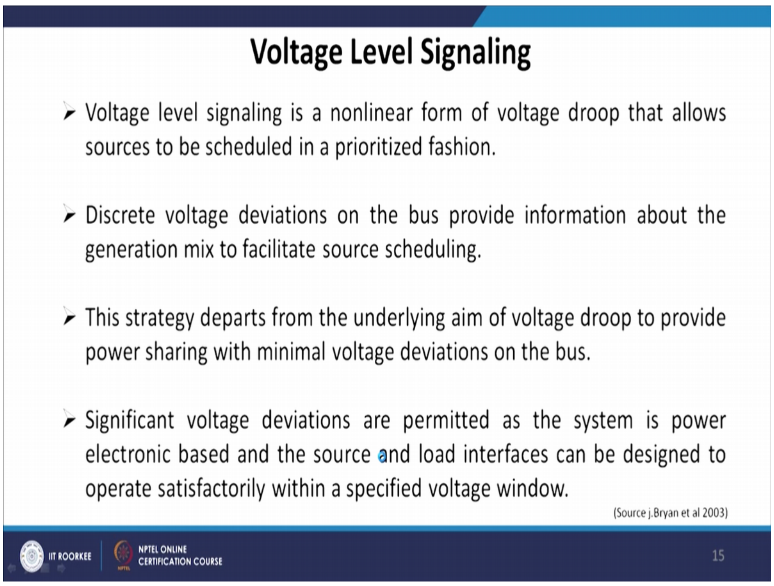

Voltage level signaling is a non-linear form of voltage droop that allows sources to be schedule in a prioritized fashion. Discrete voltage deviations on the bus provide information about the generation mix to facilitate source scheduling. This strategy departs from the underlying aim of voltage droop to provide power sharing with minimum voltage deviation on the bus. It also takes care of significant voltage deviation are permitted with the system is power electronic based in the source and load interface can be designed to operate satisfactorily within a specified voltage window.

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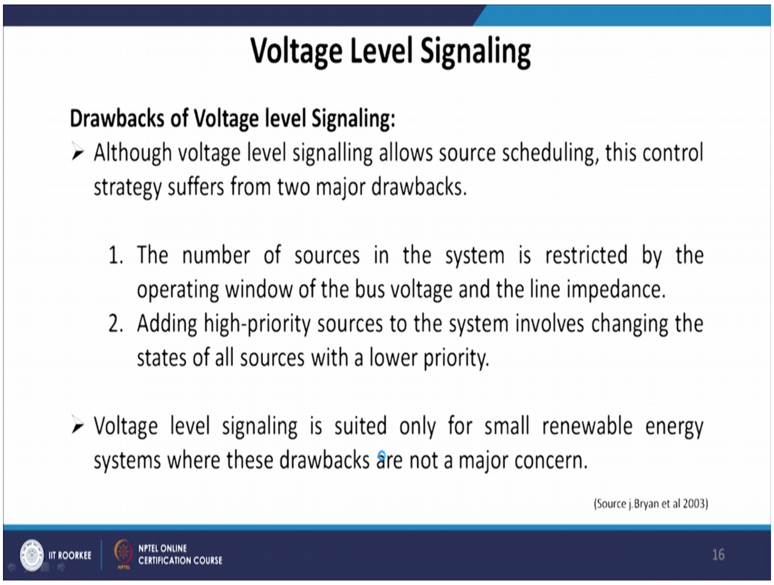

The major drawback of voltage level signaling, although voltage level signaling allows source scheduling, this control strategy suffers from two major drawbacks. The first the number of sources in the system is restricted by the operating window of the bus voltage and line impedance. What is the second one, adding high priority sources to the system involves changing the states of all sources with a low priority. Voltage level signaling is suited only for small renewable energy sources where this drawbacks are not a major concern.

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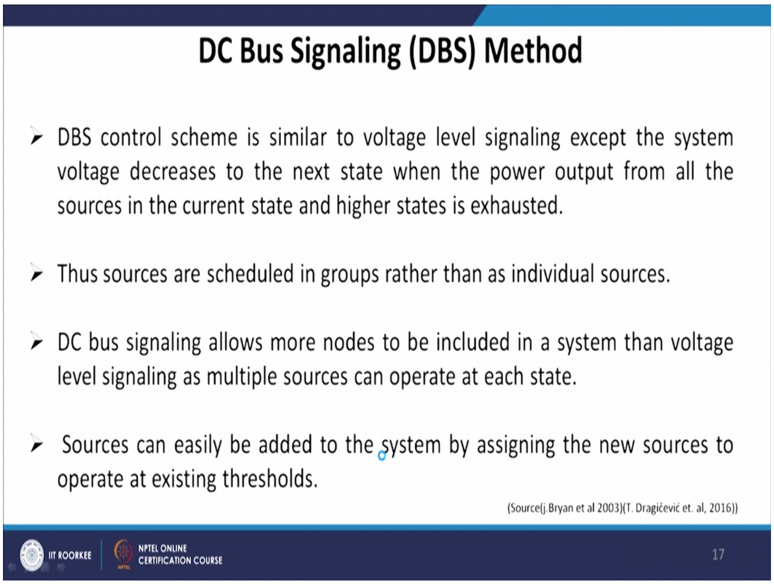

Now, let us move to DBS method that is DC bus signaling approach, DBS control scheme is similar to our fast voltage level signal expect the system voltage decrease to the next state when the power output all the sources in the current state and higher states is exhausted. Thus sources are scheduled in groups rather than as individual sources, DC bus signaling allows more nodes to be included in a system than voltage level signaling as multiple sources can operate at each state. Sources can easily be added to the system by assigning the new sources to operate at existing thresholds.

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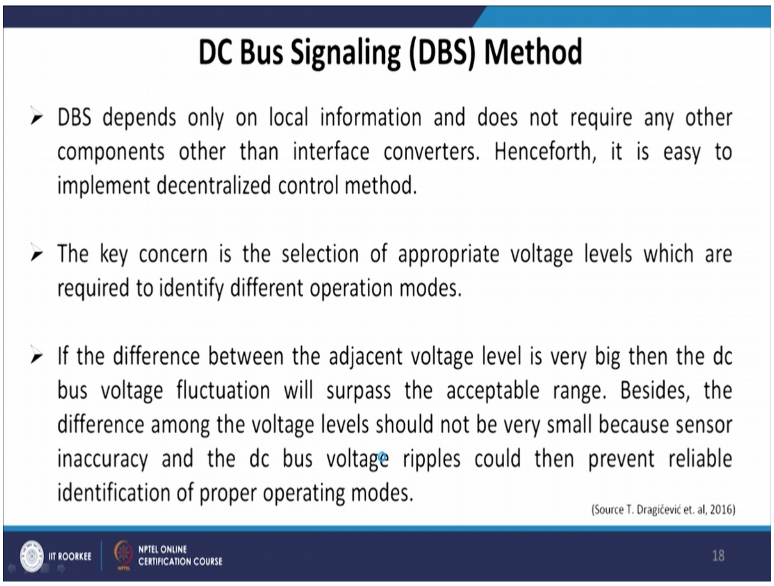

DBS depends only on local information and does not require any other than component other than interface converters. Henceforth, it is easy to implement decentralized control method. The key concern here is selection of appropriate voltage level that is whether it is 48 or 96 or 300 which are required to identify difference operation mode. If the difference between the adjacent voltage level is very big then the DC bus voltage fluctuation will surpass the expectable ranges. Besides, the difference among the voltage level should be very small because sensor inaccuracy and the DC bus voltage ripples could then prevent reliable identification or proper operating mode. So, here what is the issue difference need not be very high neither it is too small.

Now, let us concentrate on power line signaling method. So, called PLS which very interesting when we talk about power line signaling method for DC microgrid I do not see anything very special here compared to our old existing, you know power line control approach I mean the communication link is been used for our AC grid, but DC grid it is slightly different.

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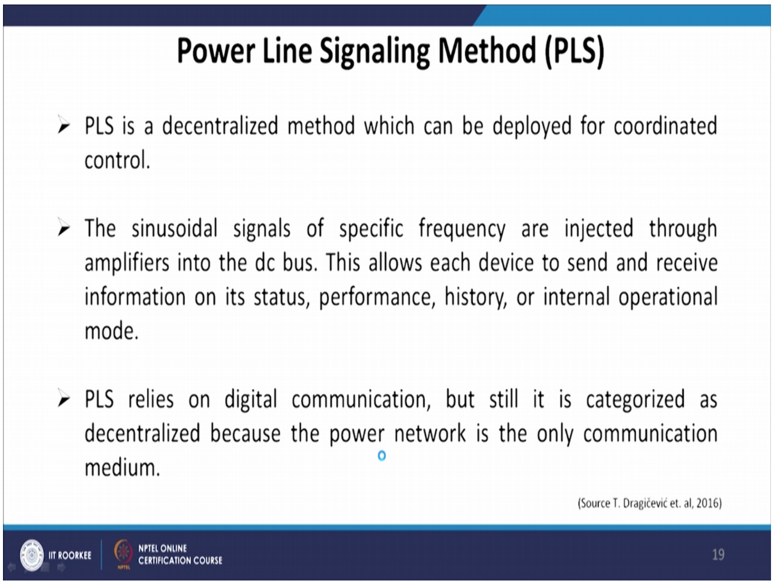

Where in PLS is a decentralized method which can be deployed for a coordinated control. The sinusoidal signal of specific frequency are injected through amplifier into the DC bus. This allows each device to send and receive information on it is status, performance, history, or internal operational mode. PLS relies on digital communication, but still it is categorized as decentralized because the power network is only communication media.

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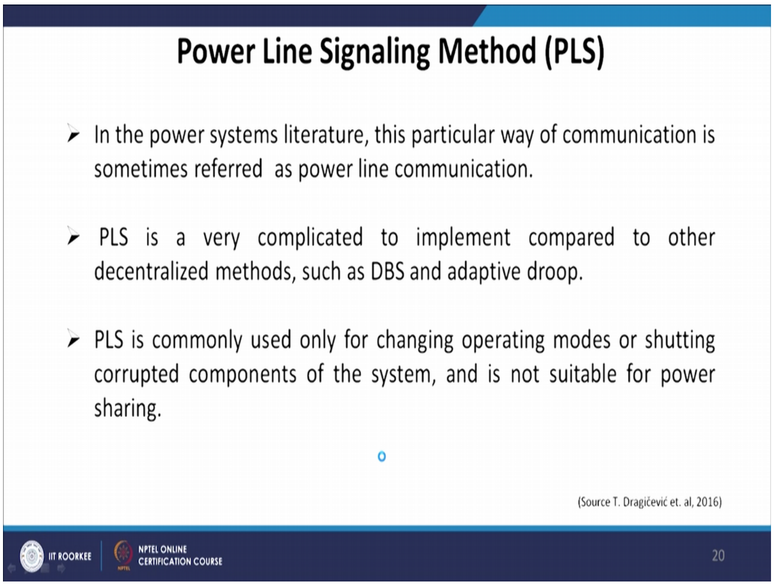

In the power system literature, this particular way of communication is something referred as power line communication as I as I was mentioning earlier I mean the conventional AC system use in the term power line communication and we here use it has a power line signaling method. So, both approach are more or less similar.

PLS is a very complicated to implement compared to other decentralized methods such as DBS and adaptive droop, PLS is commonly used only for changing operation or certain corrupted components of the system and it is not suitable for power sharing.

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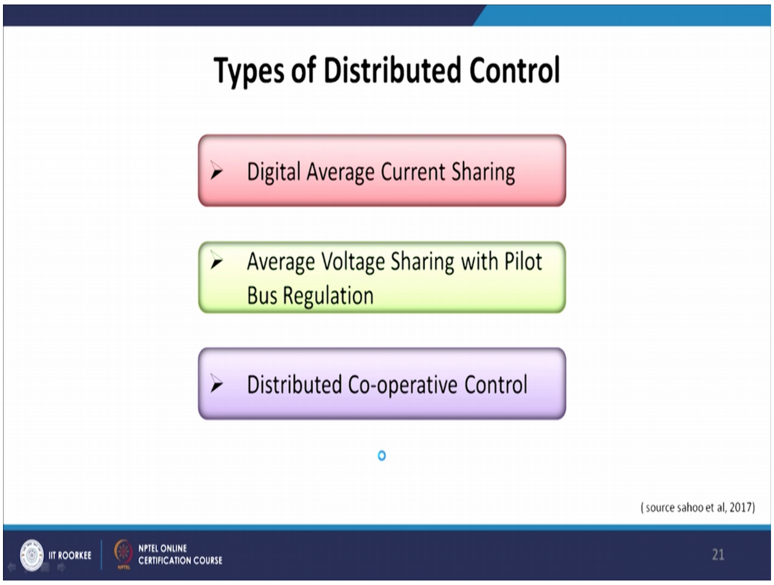

Different type of distributed control, distributed control as we have seen in my beginning of the lecture where we mention the distributed control is very smart and important and we will see different types of distributed control digital average current sharing approach, average voltage sharing with pilot bus regulation, distributed cooperative control.

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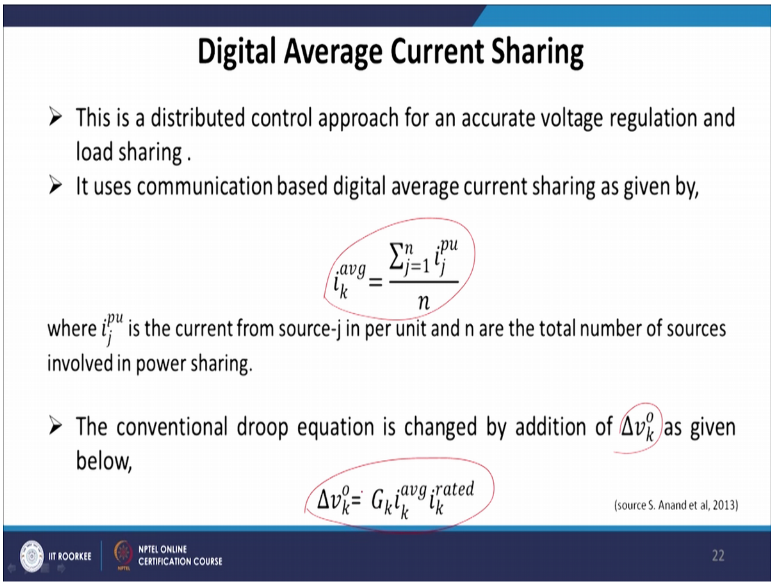

And when we move to digital average current sharing this is a distributed control approach for an accurate voltage regulation and load sharing it uses communication based digital average current sharing and the conventional droop equation is changed by addition of delta V k as given below. So, you can see the average current expression as well as droop equation being changed by addition of delta V k in this expression.

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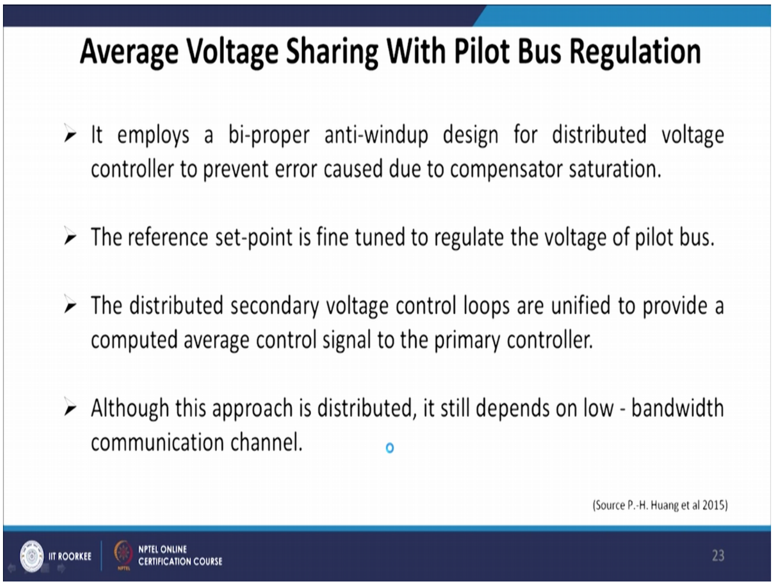

Average voltage sharing with pilot bus regulation, it employs a by proper anti windup design for distributed voltage controller to prevent error caused due to compensator saturation. The reference set- point is fine tuned to regulate the voltage of pilot bus, the distributed secondary voltage control loops are unified to provide a computed average control signal to the primary controller, although this approach is distributed it is still depends on low bandwidth communication channels.

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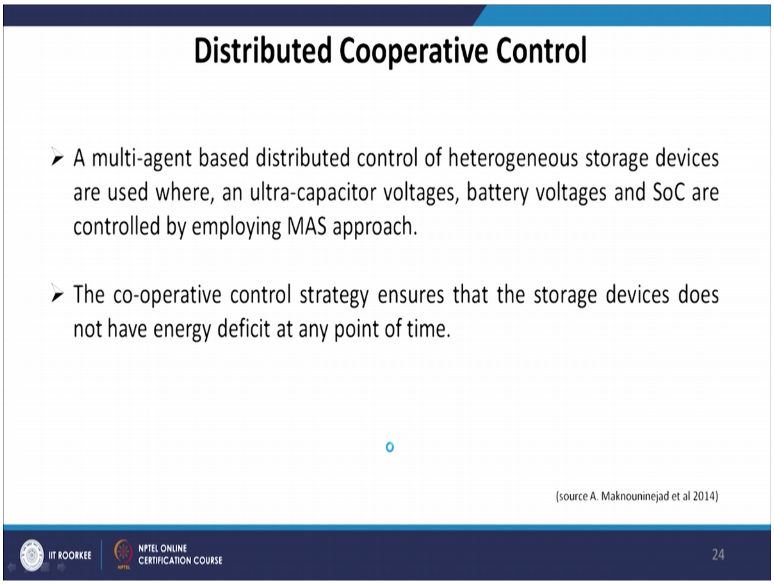

Distributed cooperative control, a multi agent base distributed control of heterogeneous storage devices are used where an ultra - capacitor voltage, battery voltage and SoC are controlled by employing MAS approach. The cooperative control strategy ensure that the storage device does not have energy deficit at any point of time.

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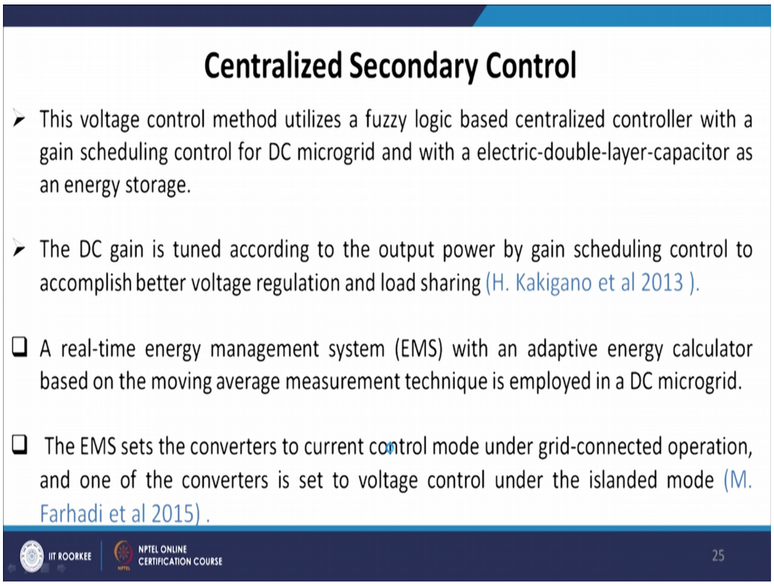

Centralized secondary control, this voltage control method utilize a fuzzy logic based centralized controller with gain scheduling control for DC microgrid and with a electric double layer capacitor as an energy storage. The DC gain is tuned according to the output power by gain scheduling control to accomplish better voltage regulation and load sharing. A real time energy management systems EMS with an adaptive energy calculator based on the moving average is measurement technique is employed in a DC micro grid.

The EMS sets the converter to current control mode under grid connected operation and one of the converter is set to voltage control under the islanded mode. Let us now summarize all the control schemes that we have gone through centralized decentralized and distributed and few important point to be noted as conclusion remarks of basic control schemes.

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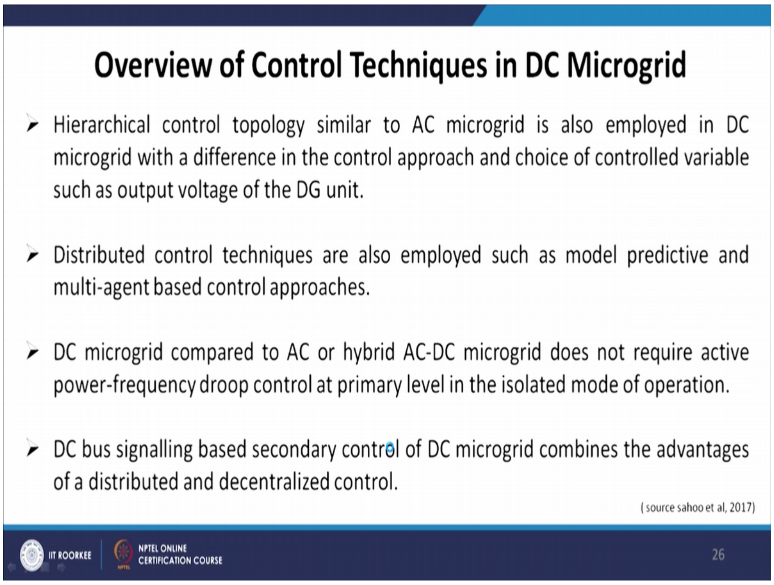

Hierarchical control topology similar to AC microgrid is employed in DC microgrid, but the major difference here is control approach and choice of controlled variable such as output voltage of the DG unit. So, control approach and DC microgrid control approach are almost similar excluding choice of control variables very importantly output voltage of the DG unit

Distributed control techniques are also employed such as model predictive and multi agent based control approaches. DC microgrid compared to AC or hybrid AC - DC microgrid does not required active power frequency droop control at primary level in the isolated mode of operation, because during isolated mode of operation it claims that it does not required DC microgrid does not required active power frequency droop signaling. DC bus signaling based secondary control of DC microgrid combines the advantage of distributed and decentralized control.

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These are the following references of today's lecture

Thank you very much.