

DC Microgrid and Control System
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Lecture - 06
AC and DC Microgrid with Distributed Energy Resources
(AC Microgrid Part Cont...)

Welcome to our lectures on DC microgrid system. We shall continue to our discussions on the remaining portion of the AC microgrid. Then we shall mostly discuss on the DC microgrid. Let us revisit that last portion of the AC microgrid.

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Control of DER Units (cont...)

- Thus the control methods for grid-forming units is suitable for both microgrid operation modes, so as to ensure smooth transients during microgrid operation mode changes.
- Grid-feeding units
 - ❖ Adjust the output active and reactive power (P and Q) based on the power dispatch strategies or the frequency and voltage variation of the load or the feeder.
 - ❖ Grid-feeding units are operated by the current-controlled mode as normal grid-connected DER units.

So we have already discussed that it is a grid fitting unit and this grid fitting units are operated by the current control mode as a normal grid-connected DERs.

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Control of DER Units (cont...)

➤ *Grid-supporting units*

- ❖ These units are controlled to extract maximum active power from their primary energy source and the required reactive power to support grid voltage sags and local demands of reactive current.
- ❖ The ac voltage control method with a repetitive control loops to compensate selected harmonics was applied, along with a modified MPPT algorithm.

Now, we shall come into the term with the grid supporting unit. So in case of the when it is connected in a grid-connected mode. This unit are controlled to extract maximum power from the primary energy sources and the required reactive power to support the grid voltage sag and local demand and the reactive current required. So, this will help us to increase the stability of the major grid.

So it will supply, it can access the sag control and it will supply the necessity whatever the reactive power required to be fed to stabilization of the grid. So because if you have a, then this grid is as of doing that control you know microgrid can take care of the reactive power flow control. Then it just can concentrate on the real power flow.

Thus the AC voltage control method with repetitive control loop to compensate selecting harmonics was applied that can be one of the applications that is the TSD or the power quality issues along with the modified MPPT algorithm so that it can dispatch the maximum power to the grid. So let us see that overall functioning of the microgrid with the grid introduction.

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Control Methods of DER Units in Different Operating Conditions

Status	Functions	Control Methods
Grid forming Units	Voltage and Frequency Control	Hybrid ac voltage and current control, indirect current control, and ac voltage control
	Load Sharing	Voltage and frequency control, active current sharing
Grid Feeding Units	Power Dispatch	Current control and ac voltage control, VOC and virtual flux, direct power control
	Real and Reactive Power Support	Unity power factor control, positive sequence control, constant real and reactive power
Grid Supporting Units	Real Power Output	MPPT
	Q Power Support	AC Voltage Control

So, this is the grid forming units, functions. These are voltage and the frequency control and sometime load sharing. Hybrid AC voltage and current control, indirect current control and AC voltage control. These are the different kind of control we may use. Then we got a load sharing, the frequency and the voltage control and active current sharing thus by active power sharing.

Grid feeding unit that is power dispatch and the real and reactive power support, current control and voltage control both that is VOC and virtual flux control and direct power control. This can be a different kind of control technique can be applied. The real and reactive power support. The control technique can be unity power factor control or the positive sequence control if it is unbalanced also there and constant real and reactive power control.

Grid supporting unit, real power output that is MPPT and PQ support generally it is AC voltage control. This is the some discussions on the AC microgrid. Now we shall switch over to the DC microgrid.

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AC and DC Microgrid with Distributed Energy Resources (DC Microgrid Part)

So while in a DC microgrid okay, we will discuss about the introduction to the DC power system.

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- Introduction to DC Power system
- DC Microgrid
- Motivations for DC Power System
- Principle of DC Voltage Control
- DC Microgrid Power Flow Control
- Practical concerns of future DC Microgrid System

And we shall see that what are the difference Edison proposed and now this is DC microgrid. And motivation for the DC microgrid system we will know (04:46) stand in AC. Principle of the DC voltage control we have seen the different kind of voltage control is described in case of the DC and now AC we will see that what can be done by DC.

This is the DC microgrid power flow control, practical concern of the future microgrid system. These are the few thing will be discussed here.

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Introduction to DC Power system

- The first electrical networks were designed to operate with DC power.
- However, due to practical challenges with implementation of dc networks, for example absence of stepping up/down dc voltage levels during that period made the utilities companies to shift their network to AC system.
- One of the main reasons for the worldwide extension of AC systems is the possibility of the voltage level conversion by the use of AC transformers.
- Whereas, a change in the level of DC voltage requires implementation of more complex power electronic-based devices that were not available in the past.

So the first electrical network was designed to operate with a DC power we all know that by Edison. However, due to the practical challenges to implement with a, the practical challenges with the implementation of the DC network, for example, absence of stepping up and the step down voltage level which can be easily done by the transformer level during that period made the utility company to shift from the DC to AC system.

Mostly due to the transformer because at that time, we did not have a very versatile SMPS or switch mode power supply or DC to DC conversion system. For this reason you are forced to go for the AC system and it has a lot of advantage of AC system, we cannot deny that. One of the main reason for worldwide extension of the AC system is the possibility of the voltage level conversion by use of the AC transformer.

And it has a very high efficiency. It is quiet rigid, resilient, the long life for this is an AC Tesla case for transformer. Whereas change in the level of DC voltage require implementation of more complex power electronics devices that were not available in the past and so Nikola Tesla win the battle because of the lack of DC to DC converter in those days.

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Introduction to DC Power system (cont...)

- However, in recent time new and efficient converters have been developed that facilitate changes in DC voltage level.
- Using these new developments, almost all the required DC voltage and current levels are available by use of series or parallel structures of new power electronic devices.
- In today's digital age, more and more devices are operated with DC power. E.g., consumer electronics, industrial information technology, communication technologies and electrical vehicles.

However, in the recent time, new and efficient converter have been developed that facilitates the changes of the DC level. We can have multiple DC level with the help of the different type of DC to DC converters. Using this new development almost all the required DC levels and current levels are available by use of series or parallel structure of new power electronics devices.

Today's digital age, more and more devices are operated with DC power for example, consumer electronics, industrial information system, communication technology, and electric vehicles. So for this reason we have huge chunk of the DC power and also we have our DC sources.

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DC Microgrid

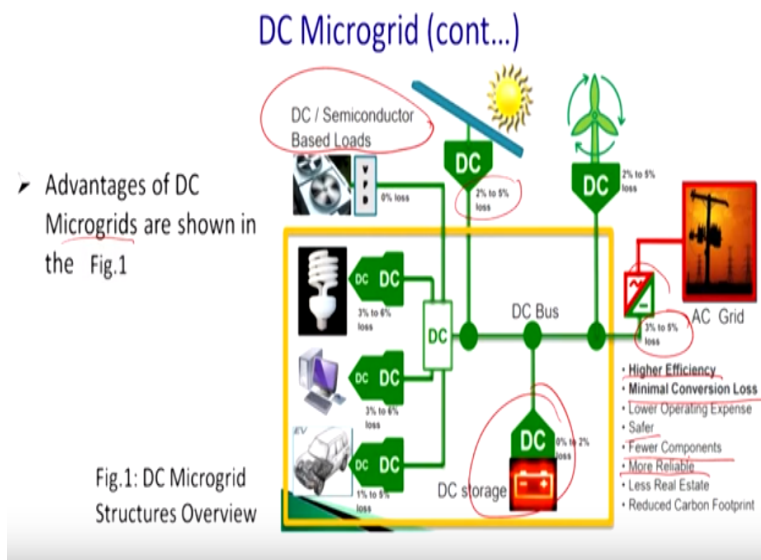
- DC Microgrid is an electrical system that can efficiently distribute, consume and potentially create and store, direct current (DC) electricity to power a wide variety of electrical devices in and around buildings when connected to a utility grid or as an island.
- A DC microgrid comprises of :
 - ❖ DC Power Sources (PV Solar / Wind / Fuel Cell / Rectifier connected to a utility grid)
 - ❖ DC Power Distribution Network(s) (Safe Class 2 wiring / Conduit / Wire)
 - ❖ DC Devices / Loads (Lighting / Computers / Electronic Equipment / Controls / Motors / Fans)
 - ❖ Controls / Monitoring (Wireless / Wired / Virtual / Cloud Based)

The microgrid is an electrical system that can efficiently distribute, consume and potentially create and store direct current electricity to power a wide variety of electrical

devices in and around a building when connected to a utility grid or as an island. A DC microgrid comprises of DC power sources, PV, wind, fuel, rectifier connected to the utility grid.

The power distribution networks, safe class 2 wiring, conduit, wire, DC devices, load, lighting, computer, electronics equipments, controls, motors, fans, etc. Controls and monitoring of wireless, wired, virtual cloud based computation, servers, and other devices.

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So this is the advantage of the DC microgrid is shown here. So this is the DC microgrid loads that is VFD, variable frequency drive. You may have a solar panel and you have only 2 to 5% loss and thus you have a DC grid. From there you can have a CFL. You can have a computer, you can have a DC batteries to run the car. Thereafter you may have a storage element and you may actually get the power through active rectifier injected into the system.

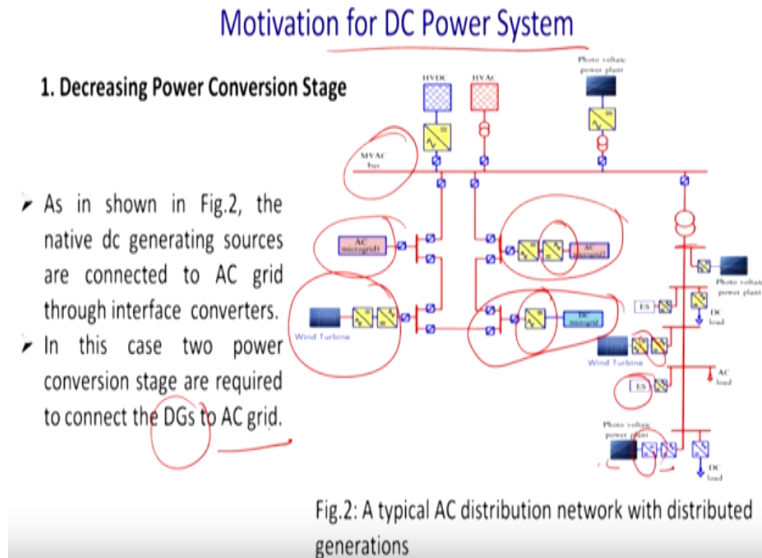
The higher efficiency, so we will, what is the cause for going for the AC? One is higher efficiency and you have seen that different kind of reactive power, real power flow to be controlled. There are many issues, frequency, drooping, all those issues comes into the picture. Minimal conversion loss, we can see that. This is active rectifier. Loss is just 3 to 5%. Lower operating expenses because you can actually get rid of bulky transformers and the transmission line. It is safer.

Generally peak of the AC is actually root 2 times more than the peak of the DC voltage. Since RMS values are set to 20 volt DC and the 20 volt AC, AC is more fatal than DC. And fewer components because you need not have to if you require to have a adjustable speed type, since your DC bus is available you put an adjustable speed type and charge it,

you run it. More reliable.

Essentially this aspect required to be proved, resilience of the DC to DC converter. Nowadays we are moving towards the all this pressure of a DC to DC converter and our designer can make more resilient DC to DC converter. For this reason it can be more reliable. Less real estate space will occupy because you do not require a bulky transformer. And reduce carbon footprint since you can use solar directly.

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So those are the few aspect of the DC microgrid and see the motivations of for the DC power system. And you know that to meet the transmission losses nowadays you talk about the HVDC line. Now you may have a very high voltage DC line and from there you can have a mega voltage bus and from there you may have a AC microgrid, you have a wind turbine, then we may have another AC microgrid and here this portion is the DC microgrid.

Same way you may have a photovoltaic cell. Photovoltaic cell is DC, you can convert into the AC and connect to the some AC buses. Thereafter from there you can have a photovoltaic plant. Again you inject in AC, you may have a energy storage system. Again you have to convert into the AC. You have a wind turbine system. You have a AC.

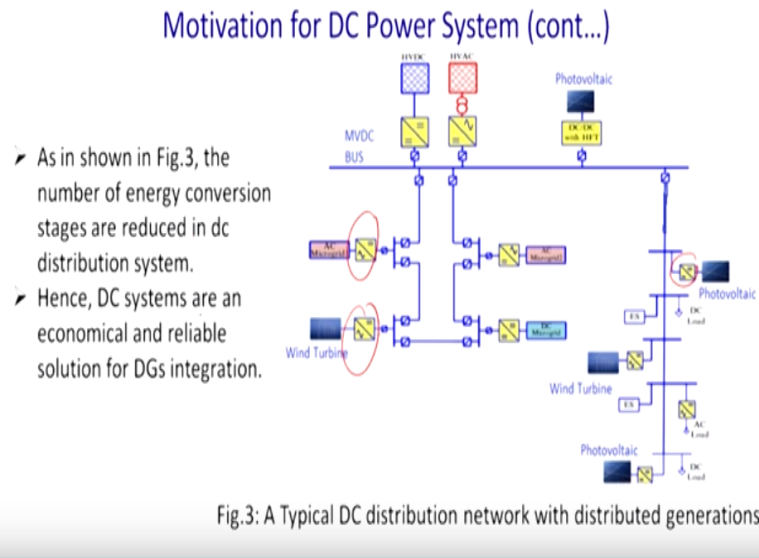
Thereafter you convert into the DC because you cannot integrate directly to the frequency that available from the wind turbine and because of the fluctuations of the wind speed. And ultimately you got a DC to DC conversion here. And then you put it and this part is also DC. And again this part is DC. You have a DC to DC converter. Then you have a AC to DC converter to synchronize.

So what we can see you know essentially this AC to DC converter, AC to DC converter is

placed in everywhere. So, why cannot we get rid of this AC to DC converter and thus increase the efficiency and the reliability of the system. As shown in the figure 2 the native DC generator sources are connected to the AC grid through interface converters.

In this case, two power converter states are required to connect distributed generator to the AC grids. So we can get rid of this extra AC to DC converter at every places by having a DC grid.

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And see that as shown in the figure 3, the number of the energy storage are reduced in the DC distribution system. Consider that DC distribution system you have a solar photovoltaic cell, you have a DC to DC converter directly put to the DC bus, you have a DC load and a electric storage element that can directly coupled and you have wind turbine, you have AC to DC conversion and directly put it.

And again you have a solar photovoltaic cell you can directly put it through a DC to DC converter. So you get rid of many AC to DC converter. And here you can see that you have put this AC to DC converter. So, you can see that number of component count in DC microgrid essentially are less. So, number of energy conversion carriers are reduced in DC distribution system.

Hence DC systems are economical since you have a less component count reliable solution for the DC integration in case of the microgrid.

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Motivation for DC Distribution System (cont...)

2. Increase the Transmitted Power by a Cable

- The power carrying capability of AC lines depends on thermal limits and required reactive power, while the capacity of DC lines mainly depends on the thermal limit.
- Due to the absence of the reactive current component, the current magnitude and cable losses are reduced when dc system used.
- To illustrate this fact, let us consider the current flowing in a line that can supply a given AC and DC voltage.
- In AC system, assume the load is single phase load that P_{ac} , $\cos\phi$ and I_{ac} its active power, power factor and current when it is fed ac source. The corresponding line current can be calculated as:

$$I_{ac} = \frac{P_{ac}}{V_{ac} \cos\phi} \quad (1)$$

Now, increase the transmitted power by a cable. So, this is the challenge you know you do not have a transmission line here in the case of the microgrid. Power carrying capability of the AC line depends on thermal limits and required reactive power while capacity of DC line mainly depends on the thermal limits only. Due to absence of the reactive power current component, the current magnitude of cable losses are reduced when DC is used.

To illustrate this fact, let us consider the current flow in the line that can supply given AC and the DC voltages. In AC system assume the load is single phase load that is P_{ac} $\cos\phi$ and I_{ac} . Its active power, power factor and current when fed from the AC source. The corresponding line current can be calculated as this one, that is $I_{ac} = P_{ac}/V_{ac} \cos\phi$.

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Motivation for DC Distribution System (cont...)

- Where V_{ac} is the root mean square (RMS) value of AC voltage. The current of this line supplying the load by DC voltage is

$$I_{dc} = \frac{P_{dc}}{V_{dc}} \quad (2)$$

- Where P_{dc} is equal to the active power when load is supplied by the AC source. V_{dc} is the DC voltage that can be considered as $\sqrt{2}V_{ac}$.
 - Since the insulation of the cable and insulators is designed according to the maximum voltage of AC systems, the load can be supplied by DC voltage equal to the maximum value of the AC system.
-

And whereas, in case of the DC where AC is the root mean square or the RMS value of the AC voltage. The current of this supplying load by DC voltage is just $I_{dc} = P_{dc}/V_{dc}$. Where P_{dc} is equal to the active power when the load is supplied by the AC sources and DC is the voltage that can be considered to be root 2 into V_{ac} .

Since the insulation of the cable and the insulation is designed according to the maximum voltage of the AC system, the load can supply by the DC voltage equal to the maximum value of the AC system. So, you can go to root 2 times higher to supply the power. Thus cable can handle in terms of the insulation higher DC voltages.

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Motivation for DC Distribution System (cont...)

- The current flowing through the line when it is connected to the dc source can be calculated by:

$$I_{dc} = \frac{\cos(\phi)}{\sqrt{2}} * I_{ac} \quad (3)$$

- If $\cos\phi = 0.87$ is assumed, the dc current of the cable is 61% of the current of this line when a load with the same active power is supplied by AC source.
- This shows that the total power of loads that can be supplied by a cable increase when DC systems are used.

The current flow through the line is connected to the DC source can be calculated by you know $\cos\phi/\sqrt{2}$ into I_{ac} . If $\cos\phi$ let us assume something. So, it is 0.87 is assumed. The DC current cable is 60% of the current of this line when load with the same active power is supplied by the AC source. So, 60% current rating is diminished, the thermal limit you can push for the higher current capability.

This shows that the total power of load that can be supplied by the cable increases when DC systems are used.

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Principle of DC Voltage Control

- Fig.4 shows the basic DC terminal model.
- The terminal voltage would rise when the capacitor charging current is positive and drop when negative.
- The voltage variation of a DC microgrid can indicate whether the system power flow is effectively balanced.
- The charging current mathematically expressed by:

$$i_{charge} = i_t - i_g \quad (4)$$

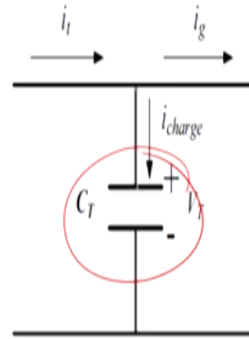


Fig.4: DC bus Voltage variation control scheme

So, let us come to the figure 4. Principle of the there is no frequency control, only there is a voltage control. This is one of the also a big advantage of the system. Figure 4 shows the basic DC terminal model. The terminal voltage would rise when capacitor charging current is positive and dropped when capacitor charging current is negative.

The voltage variation of DC microgrid can indicate whether the system power flow is effectively balanced. So you have the capacitor voltage when you see that this is only the droop control when you have you can see that voltage of the bus is constant that too in power input and power output are being balanced. The charging current can be mathematically expressed by $i_{charge} = i_t - i_g$. So from there you can control the flow of the power in microgrid. This is simple model.

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Principle of DC Voltage Control (cont...)

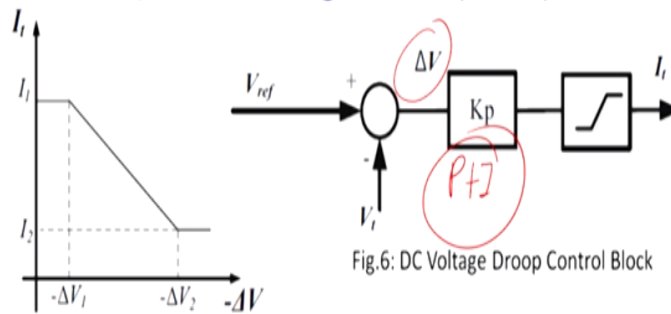


Fig.5: DC Voltage Droop

Fig.6: DC Voltage Droop Control Block

- where i_t is the terminal current and i_g the DC grid current.
- Once the grid current is given, the charging current can be regulated by controlling the terminal power.

So principle of the DC microgrid voltage control. There is no need of the frequency and

reactive power real power control. This is the droop control. We have seen the droop control in case of the frequency control in case of the AC microgrid. Here we can apply the same concept, but it is quite easier. It does not have a BCU and all those things. You can directly feed V_{ref} and V_t . You have a delta error.

Then you have a, you may have a proportional plus integral control that is PI controller. And thereafter saturation lock and you can calculate the i_t that required to be charged. Where i_t is the terminal current and i_g is the grid current. Once grid current is given the charging current can be regulated by controlling the terminal voltage.

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Principle of DC Voltage Control (cont..)

- Droop control, as is shown in Fig.5, is widely used in the implementation to determine how much current a slack terminal shall be given on a real-time basis.
- Linear current-voltage control is imposed when the voltage variation is between ΔV_1 and ΔV_2 .
- Saturation current/voltage is normally added for power rating or control band switching concern.
- The droop control can be generalized as a proportional with saturation control shown in Fig. 6.

Droop control as shown in the figure 5 is widely used in implementation to determine how much currents a slack terminal shall be given in a real time basis. Please recall your power system analysis you have slack buses so that in this case we have a slack terminal. Linear current voltage control is imposed when voltage variation varies between V_1 to V_2 . So you can have a linear control works very fine in the system.

Saturation current or voltage is normally added for the power rating or control band switching concern. The droop control can also be generalized as proportional with the saturation control as shown in the figure 6. So you can go back to the figure 6 and we can see. This is basically the droop control and this is the saturation block.

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DC Microgrid Power Flow Control

- Power flow control capability is one of the main challenges for the successful operation of DC distribution networks.
- In DC networks, bus voltages do not have a phase angle and the transmission line impedances do not have an imaginary part.

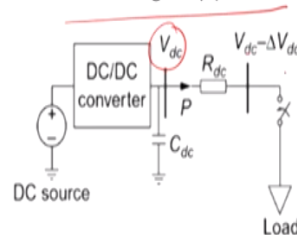


Fig.7: DC grid simplified power system

Now, come to the point of DC microgrid power flow. The power flow control capability is one of the main challenge for successful operation of the DC microgrid. The DC network and the bus voltage do not have a phase angle and the transmission line impedance do not have the imaginary part. So it is quite simple. So you have a DC source.

You may have a DC to DC converter because this is the source voltage and the load voltage may be different and for this reason you have a different V_{dc} that R_{dc} . Then $V_{dc} - \Delta V_{dc}$ and this will be the load.

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DC Microgrid Power Flow Control (cont...)

- Voltage and current are the only parameters used in the control of the dc power flow.
- In dc grid (see Fig.7), active power flow is proportional to the dc voltage (V_{dc}).
- Therefore, the active power can be controlled by the dc link voltage as described by the equation (1):

$$P = V_{dc} \frac{\Delta v_{dc}}{R_{dc}} \quad (5)$$

Where

Δv_{dc} is the voltage drop over the line resistance (R_{dc})

- In DC grid increasing load, decreases the voltage of dc link capacitor (C_{dc}).

Now the current, voltage and current are only parameter used to control the DC power flow. Now in DC grid the active power flow is proportional to the DC voltage that is V_{dc} . Therefore, the active power can be controlled by the dc link voltage and described by

this equation that is actually this $P = dc \cdot \Delta V_{dc} / R_{dc}$ where ΔV_{dc} is the voltage drop over the line resistance R_{dc} . In DC grid increasing load decreases the voltage of the dc link capacitors C_{dc} .

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Practical concerns of future DC Microgrid System

Protection Issues

- Protection is one of the main concerns about the implementation of DC networks.
- Protection issues are mainly caused by the particular behavior of the fault current in DC networks.
- Because the impedance of DC lines are lower than their AC lines counterpart, DC fault current increases very fast and this may disturb the conventional overcurrent relays.
- Alternating current circuit breakers (ACCBs) clear the fault during a zero crossing point of the fault current waveform. However, there is no natural zero crossing point for DC currents.

Now, come to the last issue, this is the protection issue. So, protection is one of the main concern about implementation of the DC microgrid. Protection issues are mainly caused by particular behavior of the fault current in the DC network. Of course, there is this issue is quite challenging, because in case of the AC you have a zero crossing that is missing here and thus you require more current carrying capability, more stopping current capability to stop it.

And because the impedance of the DC lines are lower, this is also another demerit than the AC lines counterpart, DC fault current increases very fast and this may disrupt the conventional over current relays. So it has to act very fast because since there is a inductance in the line, current will take the time to grow. But in absence of the inductance, current will go in a step fashion.

Alternating current circuit breakers ACCBs clear the fault during the zero crossing. That is what I was trying to say, zero crossing point of the fault current waveform. However, there is no natural zero crossing in case of the DC current.

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Practical concerns of future DC Microgrid System (cont...)

- Therefore, new fault interruption devices are necessary for DC networks.
- Accordingly, issues such as:
 - ❖ The behavior of converters under faulty conditions
 - ❖ Specifications of DC fault current
 - ❖ Fault detection, and fault current interruption methods are the main subjects that require more research and development

Therefore, new fault interruption devices are necessary for the DC network. Accordingly, the main concerns are the behavior of the converter under faulty conditions. Significant specification of the DC fault current, that is something we require to really find it. Fault detections and sometime we have to have a fault tolerant system also. Fault detection and the fault current interruption methods are the main subject that require more research and development because we till now we have a protection system keeping in mind of the AC protection system.

Unfortunately, we have a DC protection system. These are few challenges. So practical concern and the future of the DC microgrid, power conversion and other efficiencies will give you a more in terms of the DC but protection is one of the concern.

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Practical concerns of future DC Microgrid System (cont...)

System Integration

- In an AC grid, synchronous machine is the main device that provides active and reactive power.
- Hence the modeling of the synchronous machine dynamics is the key to successful dynamic behavior assessment of AC power systems.
- Similarly, the main component that exchanges power in a DC grid is the power electronic converter.
- In comparison to synchronous machines, power electronic converters have much faster response due to additional control capabilities and much lower inertia.
- Thus, modeling of the power electronic converter dynamics is a key aspect for assessment of the dynamic behavior of multi terminal DC grids.

So, in a AC microgrid as we can conclude our discussion in this fashion that in a AC grid

synchronous machine is a main device to provide active and the reactive power. Hence modeling of the synchronous machine dynamic is the key to successful dynamic behavior assessment of the power system. That is what people used to do for the past 50 or 100 years.

Similarly, the main component that exchanges power in DC grid is the power electronics converter. So it has been replaced by first switching power electronics converter. In comparison to synchronous machine, power electronics converter have much faster response due to additional control capability and much lower inertia. So that is aspect some extent is bad, low inertia, but fast response definitely gives you more leeway.

Thus the modeling of the power electronics converter dynamics is the key of microgrid. Is a key aspect for assessment of the dynamic behavior of the multi terminal DC microgrid, DC or AC microgrid both is applicable for AC also.

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Practical concerns of future DC Microgrid System (cont...)

System Integration (cont...)

- But, due to their switching behavior, the dynamic equations describing the converter operation are discontinuous and complicated to solve.
- To simplify power electronic converter complexity, the averaged dynamic models can be employed.
- The advantage of using averaged models is that they simplify the converter analysis while still allowing enough details to understand its dynamics and developed control strategies.

But due to their switching behavior, the dynamic equation describing the converted operations are discontinuous and complicated to solve. So ultimately you will study the (()) (28:22) of DC to DC converter and ultimately you may have a come with the different DC to DC converter in a discontinuous mode, have a, may become a minimal phase system or many complications on the control system point arises.

Thus this is a great challenge for the power electronics and control designer to solve it and if you can solve it, then there is a huge potential for the DC microgrid. To simplify electronics converter complexity, that is what I am saying, the average dynamic model can be employed, but it is an approximation. The advantage of using average model is that they simplify the converter analysis while still allowing enough detail to understand the dynamics depending on the control strategies.

So that phenomena actually the because you have a essentially a nonlinear control, because one state (()) (29:23) will be there for the DC to DC converter when switch is on and another state (()) (29:29) will be there when switch is off because it is on and off the power electronic devices that makes you a DC to DC converter. So, essentially what you can have a average model and you may have a actually a different kind of switching frequency based operation.

So average model is in approximation of this criteria considering that nonlinearity part is omitted and you can apply the linear control there. So stability is an important parameter.

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Practical concerns of future DC Microgrid System (cont...)

Stability

- There are no reactive power flow and current/voltage frequency components in DC networks.
- Additionally, active power flow depends on differences between buses voltages.
- Therefore, the stability of DC grids, which depends only on the buses voltages, has to be analyzed in a different way than for AC power systems.
- More importantly, it has to include DC passive components, and power electronic converters and their feedback controllers.

There is no reactive power flow current and the voltage frequency component in the DC network. So only the voltage control matters and the protection matters. Additionally active power flow depends on the difference between the bus voltages just bus voltage control will control the active power and therefore the stability of the DC microgrid which depends only on the bus voltages has to be analyzed in a different way than from the AC power system which we used to do in a traditional load flow analysis.

So load flow analysis mechanism we cannot apply in case of the DC microgrid. More importantly, it has to include DC passive component and the power electronics converter and their feedback controller and that worsen sometime the control strategies. Thank you. Thank you for your attention. We shall continue our discussion on the DC microgrid in our next classes.