High Voltage DC Transmission

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Module No. # 07
Lecture No. # 01

Multi-Terminal HVDC System

So, welcome to last module of this course; that is, a HVDC transmission system and this is module number 7. And in that, I will be delivering three sub topics; one is, today I am going to discuss; that is, a multi-terminal HVDC system. Second topic; I will discuss this HVDC light or also it is although trade name given by ABB and even though Siemens kept that HVDC plus. So, this basically HVDC has a different feature than the conversional HVDC, where they are using the IGBTs and we will discuss the details of this HVDC light or HVDC plus. And third part; I will be discussing about this application of HVDC system in wind power or renewable power integration issues and that will be the last of this one; this module

So, to start with, this is a lecture number 1 of this module and that is dedicated to the multi-terminal HVDC system. So, far we have studied the two terminal HVDC; means where we are having one terminal means, two stations are there, one station is working as a rectifier and another one is working as an inverter at a time, although this rectifier can work as an inverter as well and the inverter can work as a rectifier as well.

So, this we are talking the two converters because converter can work as a rectifier more or inverter more. So, we are having the two converters, then it is called two terminal HVDC link which I is already we discuss all this about the two terminal. So, there is also possibility that we can go for more than two, so, that is a multi-terminal HVDC transmission is an HVDC system with more than two converter stations.

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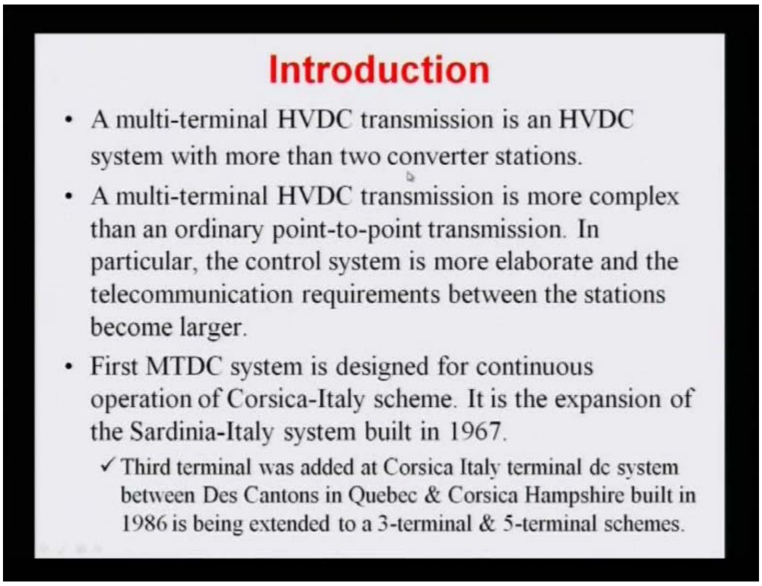

So, for example, as already I explained that in the two terminal HVDC system here, we are having one terminal here, it is working as let suppose rectifier, then another will be working as your inverter, and then it is your two terminal. Here, this is a connecter with your AC system and this side also AC system. So, this is your two terminal because terminal number 1 here terminal number 2.

But if we are putting more than two converter station that can have a different combination, it can suppose for example, if you are putting here one converter station here, then you can say now it is a multi-terminal because here you can see the three converter. So, more than two terminal, more than two converter station, you will need DC link, then it is called multi-terminal HVDC transmission system.

No doubt, this multi-terminal HVDC transmission system is more complex than the ordinary point to point or two terminal HVDC system. In particular, the control system is more elaborate and the telecommunication requirement between the stations become larger because as we know, if it is a two terminal HVDC system, here one terminal here operating as a voltage mode; it is two terminal, if one is controlling the voltage, another will be controlling the current or vice versa. So, here we require a communication channel that is, we should know which is operating on the voltage, another which is work operating as a current.

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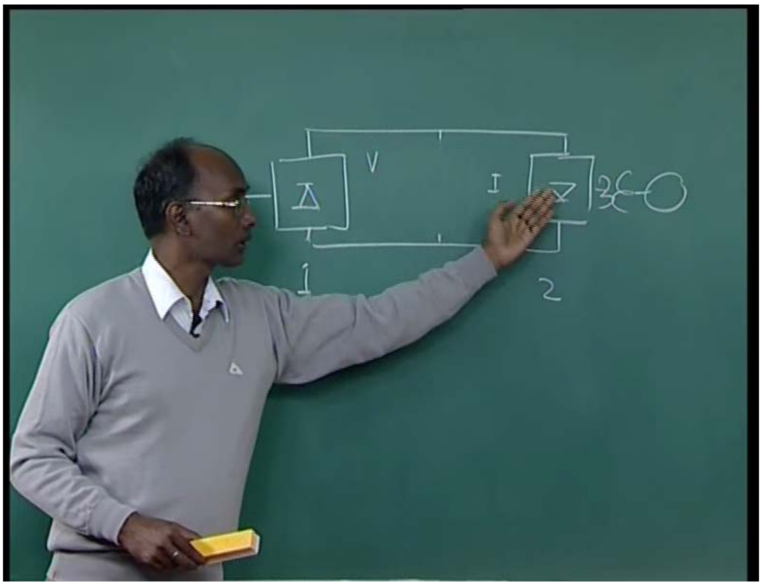

So, that information we require the communication. Now if you are going for another, then we have the communication between this converter to this converter, this converter to this converter and this converter to this conversion wire. So, we require more and more telecommunication requirement if you are going for more and more number of converter station or you can say, you are going for the multi-terminal HVDC system.

The first multi-terminal DC system which here in my presentation, am talking the MTDC; means Multi Terminal DC system is designed for the continuous operation of Corsica-Italy scheme; it is an expansion of the Sardinia-Italy system built in 1967. Basically the third terminal was added, earlier it was operating in the two terminal and third terminal was added at the Corsica-Italy terminal DC system between the then cantons in the Quebec and the Corsica Hampshire built in the 1986 is being extended to the 3 terminal and the later also is a 5 terminal scheme.

So, all though this power rating was not big, but still operating in the multi-terminal HVDC transmission system. The first large scale multi-terminal HVDC system in operation in the world is the 2000 megawatt; that is, between the Hydro Quebec and the New England transmission system and that is built by ABB in 1987 and 1982 and 1992.

The operating experience of this transmission system is very good and has proved that from a technical point of view, there are no problems to connect the several converter station to the same HVDC transmission system.

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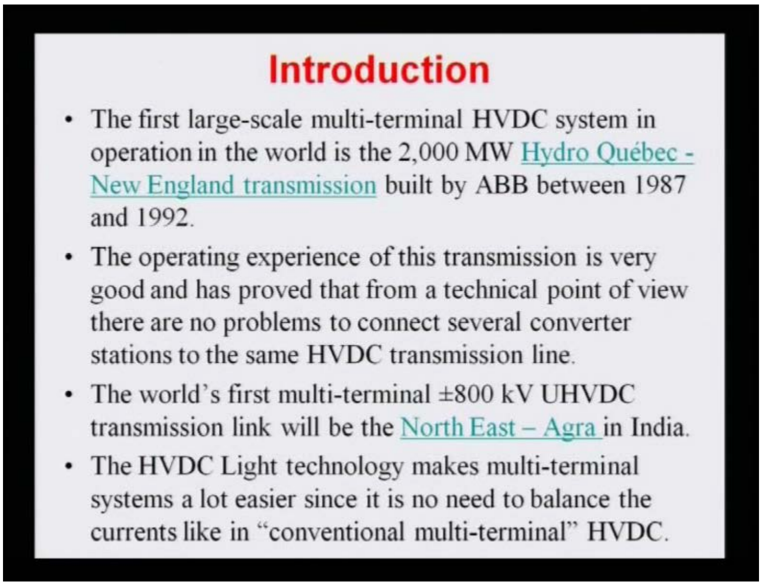

So, if you are having the two terminals that you can go for multi-terminal, you can add the converter stations and then again means you have to go for the control philosophy you have to change, also the communication requirement. So, that can operate in the multi-terminal HVDC system. So, that is the problem of HVDC system as it is said, it is a point to point transmission; means the power here, if you are just evacuating, it will be going here directly at this end, there is no intermediate tapping. So, that is why it is called point to point transmission.

But, if you are adding more converter stations or you are making this two terminal HVDC system to multi-terminal HVDC system, then you can tap the power and it was found with the experience an operating experience that it is possible only that is the cost of the complexity and also at the cost of more and more communications requirement.

So, what is the first… This is the biggest and you can say highest voltage level multi-terminal HVDC system that is a plus minus 800 kilo volt, and that is called ultra-high voltage HVDC because it is more than plus minus 500, it is a bipolar operation transmission link between the north eastern region of India and between Agra.

So, this link is still under the process, under the construction and hopefully it will be coming and then it will be the first words of ultra-high voltage DC transmission network; that is a dipole. The HVDC light technology makes the multi-terminal schemes because if we are going for the HVDC light that is solving lot of problems of HVDC as well, and that technology makes the multi-terminal system a lot easier since it is no need to balance the current like the conventional HVDC terminal system. We will see the HVDC light or HVDC plus in our next lectures, and then we will find that application of this can we going again giving the boost to the multi-terminal operation of the HVDC system.

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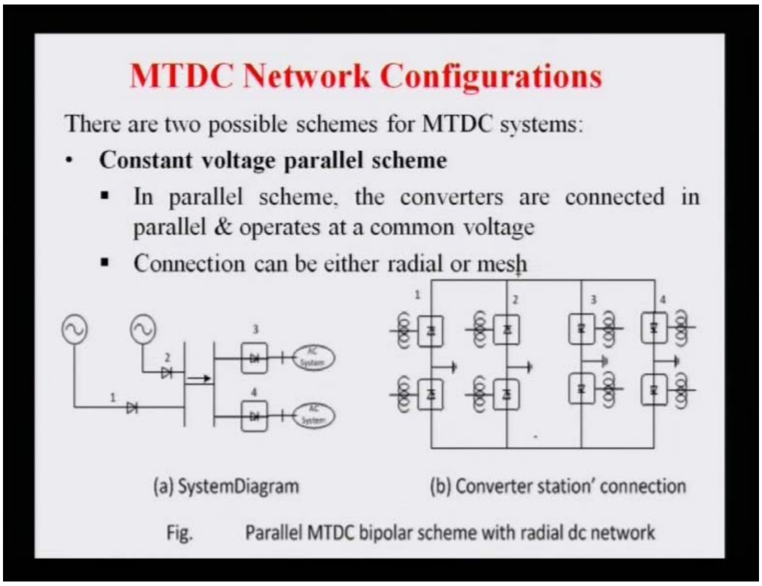

You can see this, there is a, broadly I can see the multi-terminal DC network can be classified into two category; one is called the constant voltage or the parallel scheme, and another is called the constant current or that is known as the series scheme. And no doubt; third category is also possible if you are combining the parallel series and that is called hybrid scheme where you can have the parallel as well as series combination all together.

So, let us see what is the constant voltage or the parallel scheme; as its name, the constant voltage means here the voltage is maintained, (( )) all the terminal converter stations; they are operating on the same voltage, however, the current sharing is the different principle; all the stations are sharing the different current. So, the voltage is constant.

So, in parallel scheme, the converters are connected in the parallel and operates at a common voltage; means the voltage of all this converters are same, and you can see here; that is, in this picture, that is a converter station diagram, that is converter station 1, 2, 3 and 4; here we are having the four converter stations and all these are operating in the bipolar mode. You can see this is a this is in between. So, this is a positive polarity, another is working negative polarity. So, this is a minus, this is a plus, and we are having the 1, 2, 3 and 4 converter stations.

So, you can see the voltage of this converter station; if you are talking from ground to the positive polarity or from ground to the negative polarity, all is having the same polarity, same voltage. So, that is we are operating on the common voltage. So, schematic diagram or system diagram you can see here; this is a converter 1, 2, 3 and 4; they are just can be shown in this section as well. They are connected with the AC system here 1 and 2 at this side, and the 2, 3 this side you can find here.

So, this is the parallel multi terminal DC bipolar scheme because bipolar you can see here the ground is 0, one terminal here that is a positive, another terminal is negative. So, this is called bipolar scheme. With the radial DC network, it is almost radial you can see in this configuration. So, current is flowing here to here.

Now, another category as I told that constant current or it is a series scheme. In the series scheme, basically the converters are connected in series at its name with a common direct current flowing through all the terminals; means in previous case, the voltage was same for all the terminal; however, in the constant current, the current through all the terminals are same, all converter stations is same and that can be seen here. So, this is a diagram, you can say the system diagram where you can say the DC current which is a circulating here is a constant among this converter stations.

So, in this case also, as shown in a pictorial diagram, where we are having this four terminal; terminal 1, 2, 3 and 4 and you can see it is a represented like this. And in converter station connection diagram if you will see, you can see the converter 1, 2, 3 and 4, you can see this i d is a constant which is flowing through this converters. So, i d is the constant; however, the voltage operations of these things are the value and you can find here this one DC line is grounded at one terminal; one terminal here, this is a line basically. So, we have grounded. It is basically for the specific application and this gives some reliable and secure operation of this.

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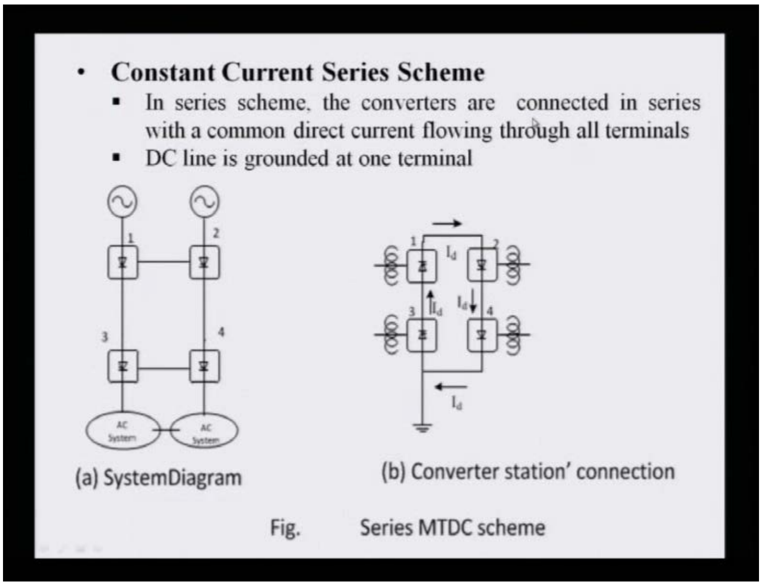

So, this is the series multi-terminal DC schemes. To combine with, we can say parallel here MTDC bipolar scheme with the mesh DC network.

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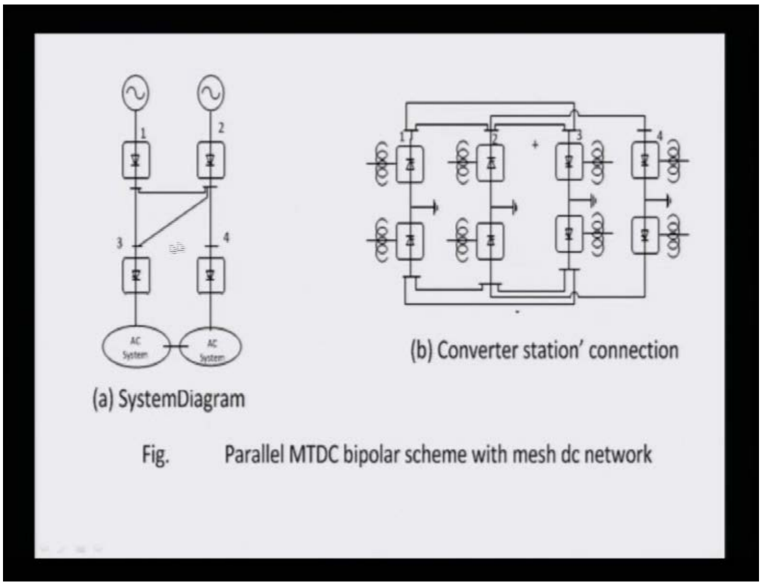

The previous was radial. Here you can see, this is your DC terminal converter station 1, this is 2, this is 3 this is 4, but here you can see the network here, it is the mesh network, it is not radial; however, in the previous case, you can say it is a radial. It is coming and going here, so this is almost radial. So, this is a radial DC network; however, we can find here it is we are having a mesh network and the connection in this.

So, if you will see the converter station connection diagram, this can be seen here the converter 1, 2, 3 and 4 because you are in 1, 2, 3 and 4. Now converter 1 you can see, it is connected here, this terminal is connected to the converter 2 and the converter 3, you can say this 1 here is connected to 2, and also it is connected to 3 whereas, the 2 is connected to 4; you can say 2 it is going to connected with the 4, and like this here, and this 1 is also connected to 3 this i said it is connected, and 2 here is connected to 3.

Similarly, you can see here also the 2 is connected to 3. So, it is a converter station connection, and that is the mesh network because here network is mesh. We are having the different voltage because this you can say this is operating at the different voltage, this is the different voltage, and this is the mesh network because they are… but if they are the radial. So, the voltage will be the same.

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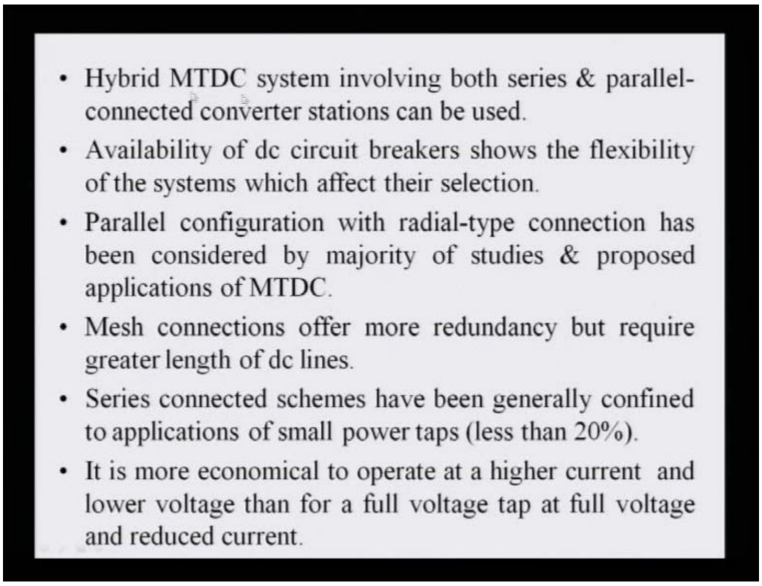

So, hybrid multi-terminal DC system involving both series and parallel connection converter stations that can be used, as I said, we can have the series only, we can have parallel only, and if you are going for the parallel and series combination, it is known as hybrid MTDC; that is, a multi-terminal DC transmission system. That is also possible.

So, availability of DC circuit breakers shows the flexibility of the system which affects their selection. Now it is having DC circuit breakers, we can flexibly operate without any problem because big problem is the DC circuit breakers; if we can use this circuit breaker, then we can operate the in flexible manner and without a lot of problems that is existing in HVDC transmission can be eliminated with help of these DC circuit breakers.

The parallel configuration with the radial-type connection has been considered by the majority of studies. Most of the studies they use this parallel configuration and proposed application for this MTDC because it is a simple and it is a very easily that can be analyze. So, that is why people are using for the studies purpose.

Mesh connections offers more redundancy, but requires greater length of DC lines because we are going for more and more lines, but it offers more redundancy, it can give more reliability of your network. Series connected schemes have been generally confined to the application of small power taps.

Normally the series connection if you will see in the series connection, what is happened, this current is constant, the voltage is changing. So, you change the power, what is happing? You have to change the voltage current is constant and that which is flowing. So, series connected scheme have generally confined to the application of small power taps because if current is… If you are going for more current, then it will be more loss you see and more voltage drop. So, the current can be minimized, same times you have the limited voltage. So, the power can be reduced and that is why normally operating less power ratings.

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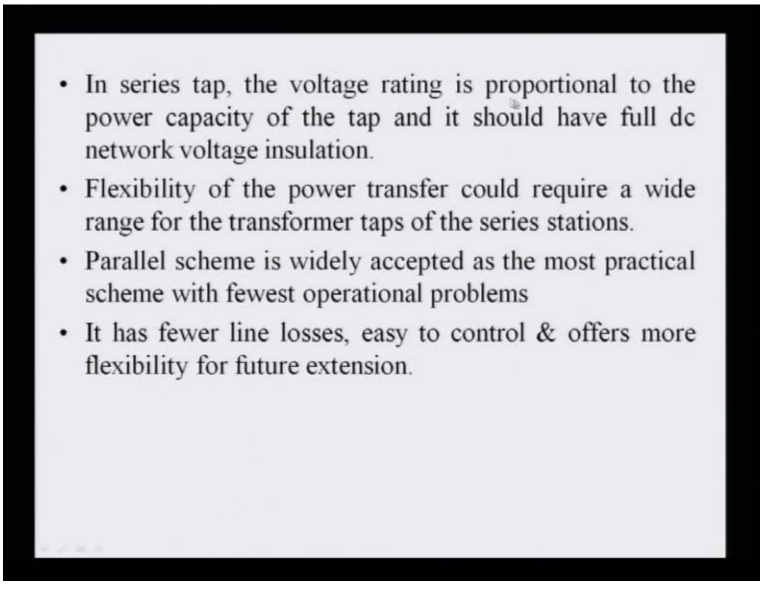

And it is more economical to operate at higher current because if you are increasing the current higher and the lower voltage than insulation requirement and also that cost of converter station can be reduced, but for the full voltage tap at the full voltage and current reduce current. In series taps, the voltage rating is proportional to the power capacity of the tap and it should have full DC network voltage insulation.

Now you can see in the series, the voltage rating is proportional to the power capacity. What does it mean, you know this DC power p here, it is your v into i and as I said, if it is a series, so, this is basically is your constant. So, what happens, you can see v is proportional to the p, whenever you are changing the v, the power will be changing and that is why it is written voltage rating is proportional to the power capacity; what capacity you want.

So, this related with this and it should have this full, have the full DC network voltage insulation. What does it mean, even though you are having the sometimes operating at the lesser power rating, but this still the voltage once you are designing the insulation level, it is the full voltage that is you have to make; weather you are modulating from higher. So, your insulation level at the full voltage level and then you can change the voltage.

So, the flexibility of the power transfer could require a wide range of transformer taps for the series stations. What we do that is another option that as I said here, if you are having the tapings, so then you can change the time and thereby you can control the DC voltage of that side. So, no doubt, these are the DC voltage here, then DC current.

So, we can also option that we can reduce the voltage by using the taps, we can also flexibly operate and we can control the power in the series stations; however, the parallel scheme is widely accepted as the most practical scheme for the fewest operational problem; it is a most widely accepted although there some problems in this multi-terminal operation, but it is most accepted.

It has the fewer line loss, easy to control and offers more flexibility for future extension. as I said, the line loss is minimum in the parallel scheme, why, because in the series schemes, we are putting this constant; however, this is a parallel and if I will say p series, in the series, it is we are also we can write the d c into i d c. Here what happen, this is the constant and i d is changing. So, what happens, your loss; that is, i square r is changing, your loss is going to be less.

So, when you are operating at the highest power level, it is highest loss and for the remaining period, it is going to reduce, but here whatever the power you are operating, the current is constant. So, i square r loss is constant and that is why you are uncurling more and more loss. So, the parallel operation will give lesser loss. So, means more efficient and also it is very easy to control the parallel operation here, because we can change the current, we can the d c voltage maintain, we can tap the currents and we can control.

So, the control becomes very easy and we will see later on that how the control becomes easy in the parallel operation, and also it offers the flexibility in the future expansion because what happens, now this voltage is maintained, you can add here as for very easily I can say here we can add another, we can add another here terminal and that you can say just like looking like a parallel operation having the four terminals multi terminals and this is a call the multi-terminal DC transmission.

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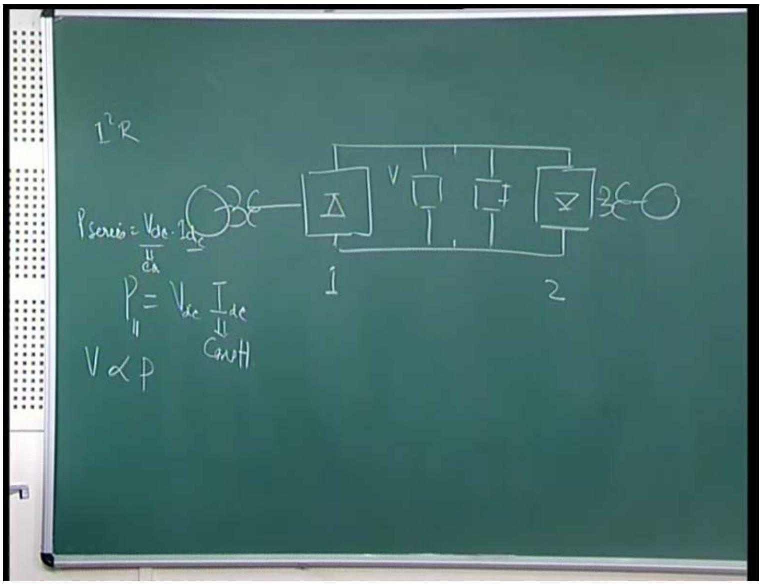

So, you can see this voltage is same very easily we are adding that only the current sharing is change and then we can change the control philosophy and then we can operate in the very successful manner. So, it is very easy to expand; however, in that here the diagram if you will see, in this diagram if you are adding here, in this diagram, if you are adding one converter, then you have to see what will the voltage drop and how to change the voltage rating of all this things. So, the voltage of all this, we are going to change; however, here voltage operation is voltage is same, current is changing, here we are making the current constant, but the voltage is changing. So, it is a slightly difficult to add in between.

So, the parallel schemes are better in and that is used for the most of the practical applications and due to the various reason, it is more efficient, easy to control, have a better flexibility for the future extension, and also as I said that is we can use the transformer tap also for the voltage control etcetera here. So, these parallel schemes are better compare to the series schemes.

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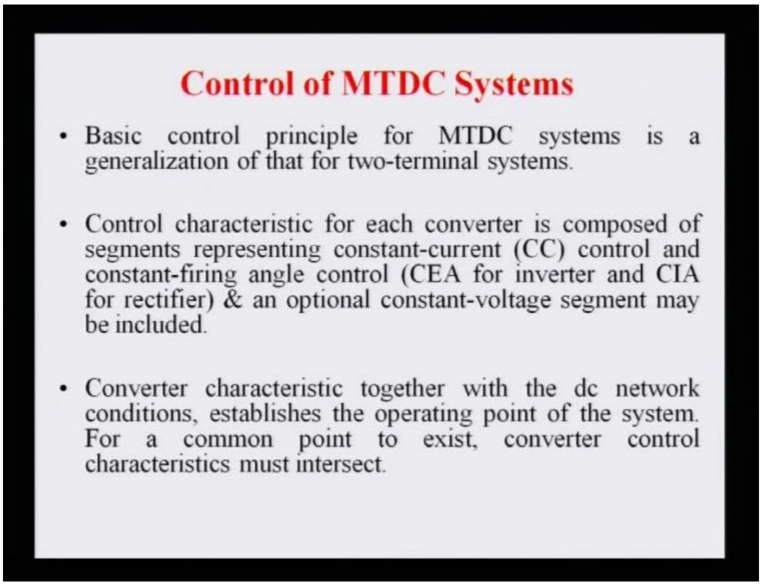

Now, let us move to this control of multi-terminal DC transmission system. As we know the basic control principle for the multi-terminal system; it is a generalization of the two terminal HVDC system. No doubt, as I said, here in the two terminal system here, if there is no multi-terminal here, the control scheme if you will find how we go for the control, this you are having the control characteristic, if remember already we discuss in our module 3, here this is your c i a; that is a constant (( )) angle, constant ignition angle control, and then we are having here CC; that is for your rectifier.

And then we had if remember here we had another, it is called CEA control; that is a constant extinction angle control, this is for your inverter. And then we are having some beta control, if remember, this is a beta control, then we are having here CC, even though we can have some constant voltage control as some people suggested the constant voltage control or may be the constant beta control, that is a both are applicable, and the then it was found that is for the lower voltage, we can basically keep this here and this is we can provide this v d c o l, and this is called voltage dependent current order limiters; that can also put at the lower voltage.

So, you can see this is a control characteristic, this is your rectifier characteristic, we are operating CIA constants ignition angle control, then CC, here we are having constant current control, then we can have the constant voltage or constant beta control, then we are having the CEA; constant extinction angle control. For the lower voltage operation which may require sometimes and our converter station converter should not be stressed to much we provide the voltage dependent control current order limiters that will reduce power rating and we can operate during the emergency or some other problems.

So, we are having the dedicated one is controlling one option then another is controlling; here one is controlling voltage, another may be controlling the current or vice versa, you can say always the control aspect is the intersection of this two characteristic will give you operations.

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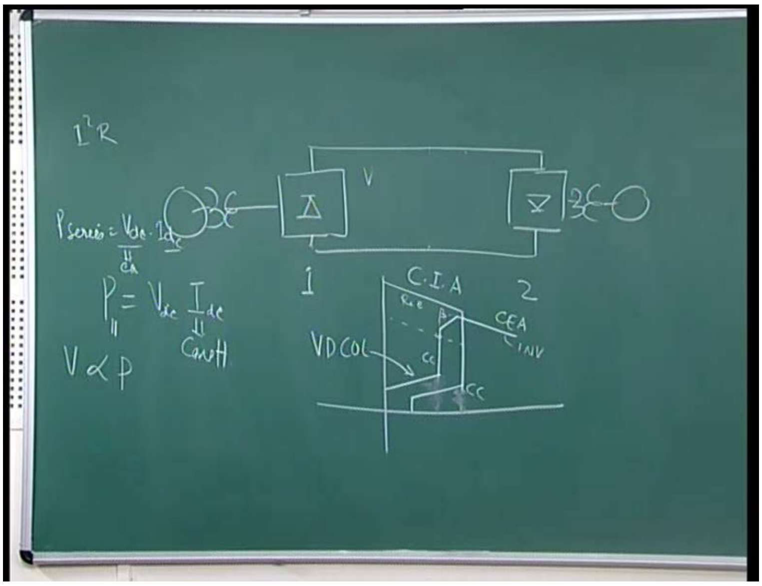

Now for example, you can see here the rectifier is operating on constant current; however, this is operating on CEA volt or vice versa. If the voltage is reduced, sometimes we can go here and you can see this is intersection, then this is operating your CIA and the inverter is operating on the constant current mode.

So, I mean to say that this is a multi-terminal DC transmission system is a basically generalization of the two terminal control and we will see our next slides. So, the control characteristic for each converter is composed of the segments representing the constant current, that is, a CC control, then we are having the constant firing angle; that is a constant ignition angle control and that is basically the CEA for inverter and CIA for rectifier, and an optional the constant voltage segment may be included and that is a optional which I said this characteristic is constant voltage or constant beta segment can be included.

So, this characteristic for all this stations will have the characteristic all together because one may operating; if it is operating as a rectifier, then take this characteristic. If it is operating inverter, then we can take this characteristic and vice versa. So, what the number of your terminals, we can have the number of characteristic because same converter can operate as rectifier and as inverter. So, we will see there in the later slides.

The converter characteristic together with the DC network condition establish the operating point of the system and for a common point to exist, a converter control characteristic must intersect, as I said that is to have the successful and stable control operation, we should have the intersection of these two characteristics. If this is your suppose rectifier, so, this characteristic if it is inverter, this characteristic they must intersect. And here basically we provide some current margin so that there should not be over lapping here. So, that margin is pasty margin is given.

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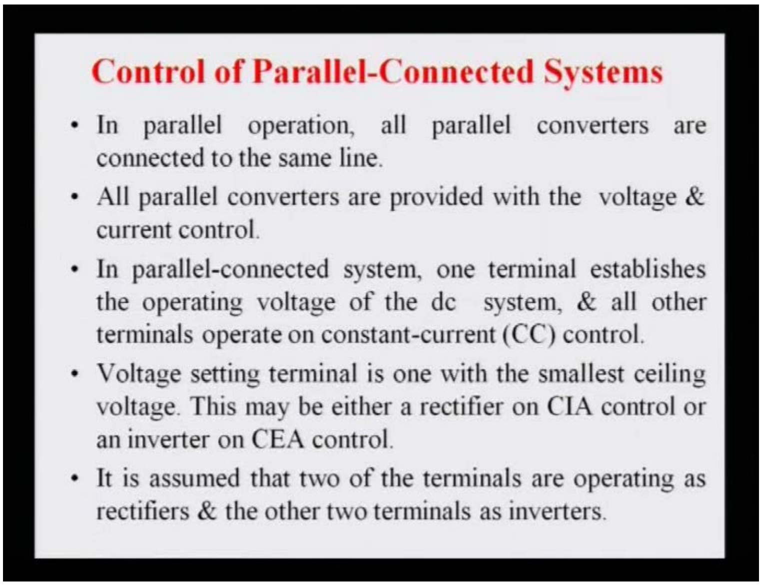

In the parallel operation, now we can go for the multi-terminal dc control aspect. In the parallel operation, all the parallel converters are connected to the same line as I said. It is connected in the same line. The parallel converters are provided with the voltage and current control. They can control voltage, they can control current; this is provided.

In the parallel connected system, one terminal establishes the operating voltage of the DC system and all other terminal operate on CC mode; means here if you are having another terminal for example, the 2. So, if one is out of these three is operating, it is maintaining your voltage, other will be operating in the constant current mode so that because the voltage is maintain by this one, and then current will be the share; whatever the current is going, that will be shared here and they will operating that current constant current mode.

So, if it is a DC here, the current; I can say DC, so, this is i d c 1 here, and this is i d c 2. So, this will be i d c is equal to i d c 1 plus i d c 2. So, this is maintaining your voltage. So, i d c 1 will be maintained by this, and i d c 2 will be maintained by this, another one. So, that is why it is said, in the parallel operation, one will be operating under voltage control, and another will be others will be on constant current control mode.

The voltage setting terminal is one with the smallest ceiling. Now out of three, who will be your voltage control and for that, normally it is the voltage setting terminal is one with the smallest ceiling voltage which have the smallest voltage will be used as the voltage control and this may be either rectifier on CIA control or an inverter on the CEA control. We will see. It is, in the given example, I am going to show one example, where we have four terminal HVDC system is there in which it is assumed that the two terminals are operating as a rectifier and the two are operating as inverter.

You can see here and their control characteristic are you can see here; this is a rectifier characteristic having the CEA and he is know this rectifier will have a the CEA and the constant current control, this is your rectifier 2; it is a CIA and the CC that is again the constant ignition angle control and this current control. And we are having the two inverters; 1 is here, inverter 1 that is operating on the CEA; that is, a constant extinction angle control and the constant current control, and another is also operating here only it is magnitude and the slow of CEA is different, here also you can find the CEA slope and here is a different.

Now, to find, this is basically the individual converter characteristic which is operating. No doubt if this is also operating in inverter mode, so, this will again shift from the CIA and CC mode to CEA and CC mode. It is like inverter 1 and inverter 2. To have this, what we to have a common characteristic, what we do, we combine the rectifier characteristic in 1 and the inverter characteristic 1. So, you can see, if you will combined here, since it is a parallel operation, mind it because we are talking the parallel operations, so, voltage is constant. So, you can see the voltage line the dotted line here.

For a given operating voltage, now you can say this is operating in the CEA CIA mode, this is operating in the constant current, this is operating in the constant current and this is also operating in the constant current which I said in the earlier slide that, one is operating at the constant voltage and that is controlling the voltage and others are operating at the constant current; means CC CC CC and CC C here.

To see what will the voltage etcetera, what we can do, we can combine the characteristic of rectifier 1 and rectifier 2 in 1, and now you can find this one characteristic. You see this character is slope, then there is a it is heating the constant characteristic constant current, now it is a lesser. So, it is coming here, then again we are having this characteristic and then finally, it is a constant current control.

So, you can find at here, this characteristic the slope you can find here, this is coming, then the constant current, then we are adding. So, we just added. So, this is a combined characteristic of rectifier. Similarly, we can have the, this is a current here is a constant, you can say this value and this value that can be shown here are equal, although it can have the different one as well because the different current regulations can be possible, margin we can give the different, here you can say the id 1 and id 2 are different here although in this figures, we have can take id 1 and id 2 same. So, what happens, this will be for same id, we are having this characteristic that is constant current and these two characteristic are added, then this will give a different slope.

So, here this characteristic here is your combined inverter characteristic, and now you can say intersection of here is mind it, intersection of here is basically this actual operating. Now what is happening.

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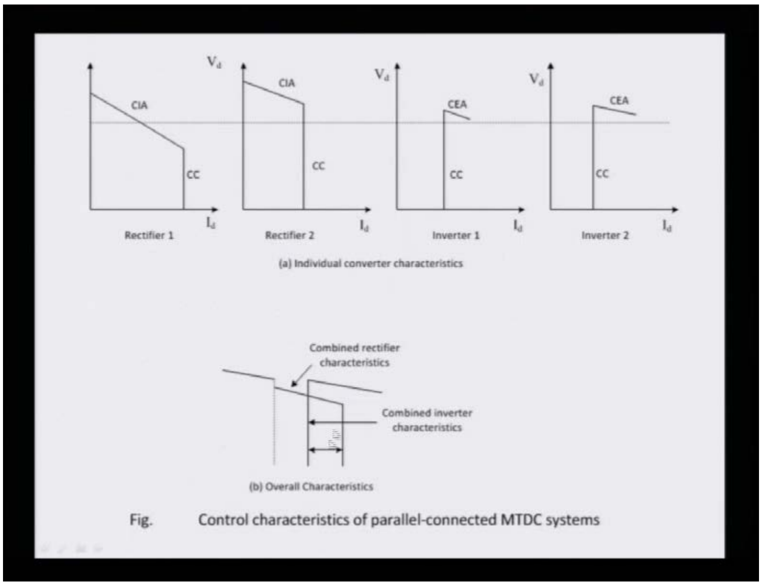

Now, what you can see, once you are operating here, so, your… This is a characteristic of this, so, it is operating on CIA, and others are operating in the constant current control here (( )) oh sorry, here this is operating on CC and CC and this is also operating on the CC. So, this is operating on the constant current and this is the overall characteristics and then control characteristics of the parallel connected multi-terminal DC systems.

In this diagram, basically, we consider the only for one pole. As I said, if it is a multi-terminal DC system, So, then you are having the two terminal, and then accordingly you can have the control characteristic. Also we did not consider the v d c o l; that is the voltage dependent current order limiter has not be consider for the simplicity; however, I said that it can be at lower operation here, that we can have the v d c o l characteristic; however, only I showed on the top of the portion here, but if you can go for the lower voltage, this characteristic also can be added and for the simplicity, I did so in the our combine characteristic here.

It is also assumed that each terminal has the only two modes of operation; that CC will be there in all these terminal, and then either of CEA or CIA will be. So, if it is a rectifier, then CIA CC, if inverter it is a CEA and CC. The voltage control option is not considered; we are not controlling the voltage. It is assumed that rectifier 1 is a voltage setting terminal because it is operating in the CIA mode. You can just sit here, this is a here or for this voltage is working the CIA mode, from here also you can see it the CIA mode, the tap changers keeps angle within the desired range.

To maintain the stable voltage, stable control operation, a positive current margin must be maintained and that margin as I said here, you can see this, we are putting some margin here that margin is coming all the… This is a current margin. So, from this current this current, there is some margin that will give you stable operation and that is a positive current margin must be maintained.

If an inverter is at the voltage controlling station, there is the possibility the voltage is at this CEA mode and then it is a vulnerable to inadvert overloading. If you are going there, so that is possibility that it is overloaded and it is unable to control the current at its terminal in the event of the system disturbance or the overload. So, this is a very difficult if the inverter is operating in the voltage controlling station.

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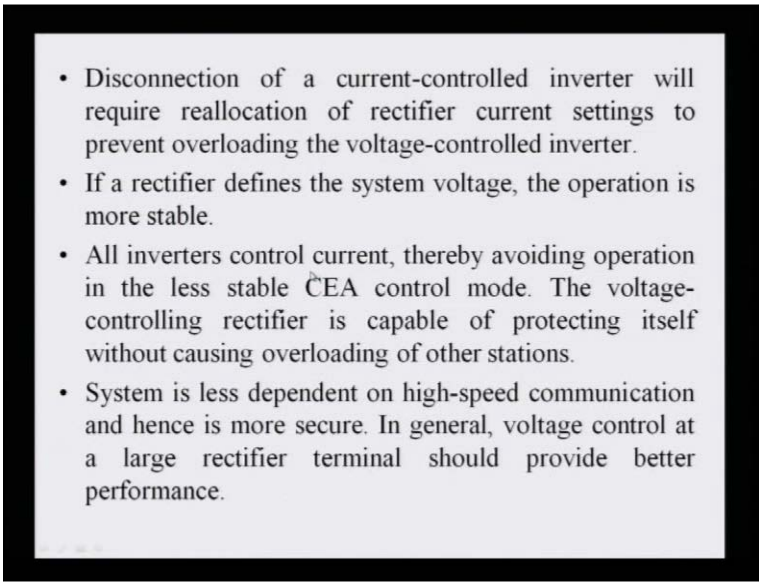

The disconnection of a current control inverter will require the reallocation of rectifier current setting to prevent the over loading the voltage control inverter. So, what happens, the disconnection of the current control inverter will require reallocation of current settings here and there; that is also is a difficult task. If a rectifier defines the system voltage, operation is more stable. So, that is why we want that is rectifier should basically operate the system voltage and that is why because more stable.

All the inverters control currents, as I said, if is in CC mode, thereby avoiding the operation of the less stable CEA control, the CEA control is constants extinction angle control; that is a constant gamma and that is a because there is any problem during this commutation here, then inverter will be in not a stable mode. So, we want that they should operate in the current control in the normal case.

The voltage controlling rectifier is capable of protecting itself without the causing overloading of other stations. So, whenever there is problems and then the voltage control rectifier can protect itself by causing the overloaded of other stations.

The system is less dependent on high speed communication, hence it is more secure. Here you can say in the parallel operation, that is, one station is controlling this, others are controlling currents. So, the communication requirement is also limited, I said one is idc 1 and another is idc 2, and this is a very easy that that it can operate. So, in general, the voltage control at the large rectifier terminal should be provided better performance and that is that is the case.

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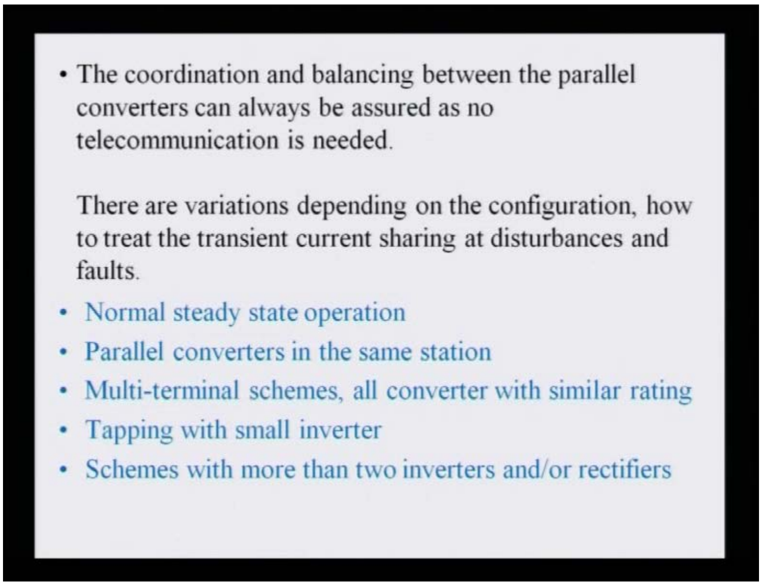

Another here, the coordination and balancing between the parallel converters can always be assured as no telecommunication is needed because here, I can say the balance here the idc here which is required by this current will be if it is they are operating as a inverter here, so, it is always balanced. So, if you can maintain this one, so, this DC is flowing and this automatically it will be taking care without even communication requirement, but since we require the communication because sometime they have to exchange their operation, one is controlling voltage; may be going to the current control mode here and there during the event of communication commutation failure or the mall operation of the converters in that case.

There are the variations depending on the configuration, how to treat the transient current sharing at the disturbances and the fault that as I said that is if there is any disturbance, mall operation of the converter, then how they are going to share that is different configuration and different operations or and different way, make an issue to handle this situation is already suggested in the literature. We are having the…

Now you can see the what are the various type of operations; one is no doubt, the normal steady state operation where as I said, the converters 1 rectifier should be on the CIA, and others rectifiers along with all the inverter should work in the CC mode; that is your normal steady state operation.

The parallel converters in the same stations, if the two stations are there, then we have to see which one will operate the voltage and which will operate the current because they will be communicating to other converter stations. The multi-terminal schemes; all the converts with the similar rating, there is a possibility that is here the multi-terminal scheme, all the converts having the similar rating. So, then who will be taking what. Also the tappings with the smaller converters; because the tapping change which is smaller converter station, how to control those. So, this is one concern here. Scheme with the more than two inverters and the rectifier, then situation becomes more and more complex. So, all these things should be the different scenarios are there and that must be addressed accordingly.

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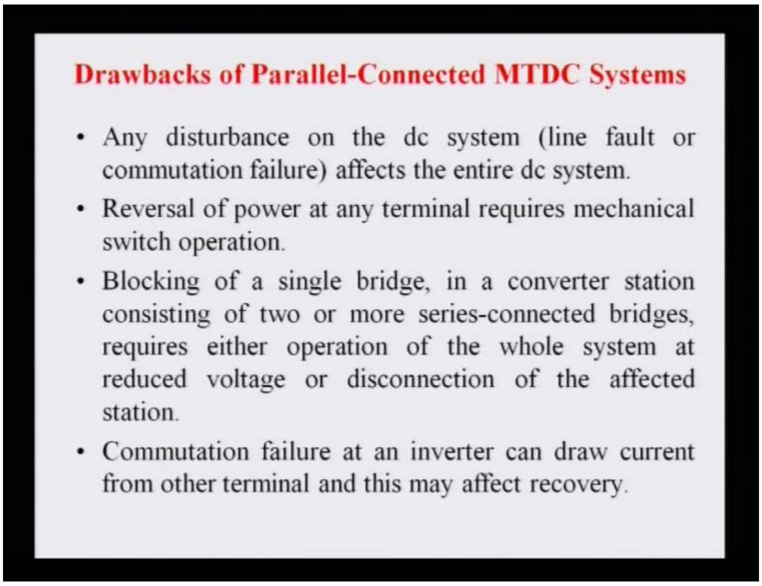

So, we saw the advantage of parallel connected multi-terminal DC transmission system. Let us see as I said some of problems as well in this the parallel connected multi-terminal DC transmission system as well. To understand this, we can see this four bullet points.

So, first one you can see; any disturbance on the DC system that may be a line fault or the commutation failure affects the entire DC system. As I said, that is disturbance may come in the transmission line; that is a d c transmission line and if there is any problem in the commutation failure in inverter, normally as I said already, we explained in the various module, that inverter commutation failure is the major concern of the inverter stations. So, that will affect the entire DC system and therefore, that is one of the problems with this parallel connected MTDC.

The reversal of power at any terminal requires the mechanical switch operation. What does it mean, let suppose, you are having this two terminal, and I can just make it the multi-terminal here. This is your rectifier operation, and then you are having here the inverter operation at this end. So, this is a two terminal; if you are having another inverter operation here, now it becomes a three terminal and of course, it is a multi-terminal as well.

So, if here, this is your power; that is, i going here, that is id here, we want this idc 1, here if you are going for idc 2, now this voltage which is the DC here, the voltage is a single pole operation I am talking, the power which is feed here; that is, going from the rectifier to the inverter; this pdc is nothing but your v that is a d c voltage here I am talking into your i d c. This power is feed from the rectifier and it is going to the inverter as well here.

Now if I want to change the power here, reversal means here if I want to I want to inject the power, what will happen? We cannot change the direction of current because in this the current direction is decided; only we have to change the voltage polarity.

So, whatever here which was here, this is as I said, this is positive and negative. So, the power was drown from this inverter and going to the AC system here as well. Suppose you want to make this as a rectifier, you want to feed the power or power reversal. So, this will be required the complete swapping because current you cannot change. So, what will happen? You have to require a mechanical switch so that you can change and this will be operating in this rather than in this mode here, I can say this is your, this is and this is positive, this negative and this becomes a rectifier.

So, we require the mechanical switch for the reversal of power in of any of this device. It is not possible here; however, when we had the two terminal, it was very easy for example, you can see that is it was possible that we can slowly maintaining the current, we can change, we can shift this rectifier to the inverter and this inverter can shift to the rectifier, and then we can have the power reversal from one direction to another direction without having the mechanical switch, but here it is not possible. No doubt the current margin is to be change; already we saw the control characteristic of your rectifier and inverter. We require some change in the margin that will be done, but it is very easily we can transfer, but here in the multi-terminal as I said, you require the mechanical switch operation to change some direction of power; that is, the power reversal.

The blocking of a single bridge, suppose you are having the multiple bridge operation, you are having the two bridge or you are the having the different converters here, then in a converter station consisting of two or more series connected bridges require either operation of whole system at the reduced volt or the disconnection of the affected station.

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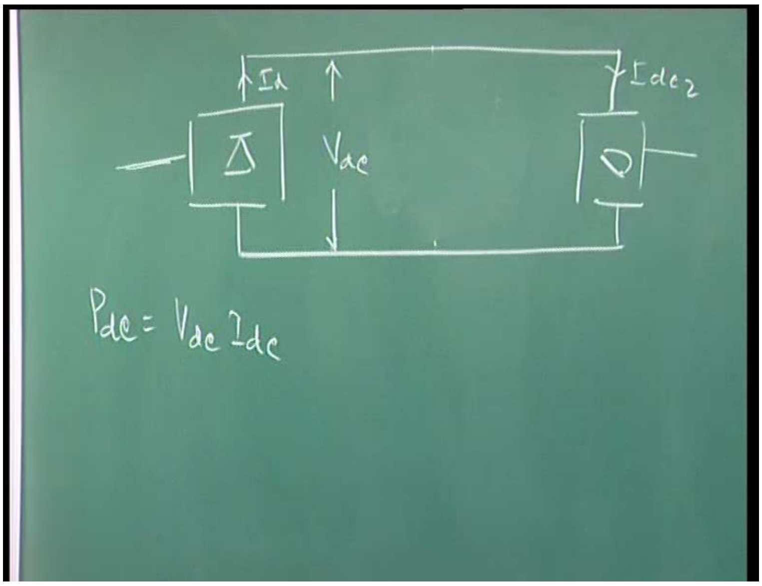

So, here to if you want to bypass you are take it for the block this single bridge for the various reasons; suppose you want to block and take it out for the maintenance another operation if there is some problem, then you have to may be possibility that you can block the complete or disconnect the complete station in this one and then you can go for the operation for other as well. So, the communication failure at inverter can draw the current from the other terminal and this may affect the recovery.

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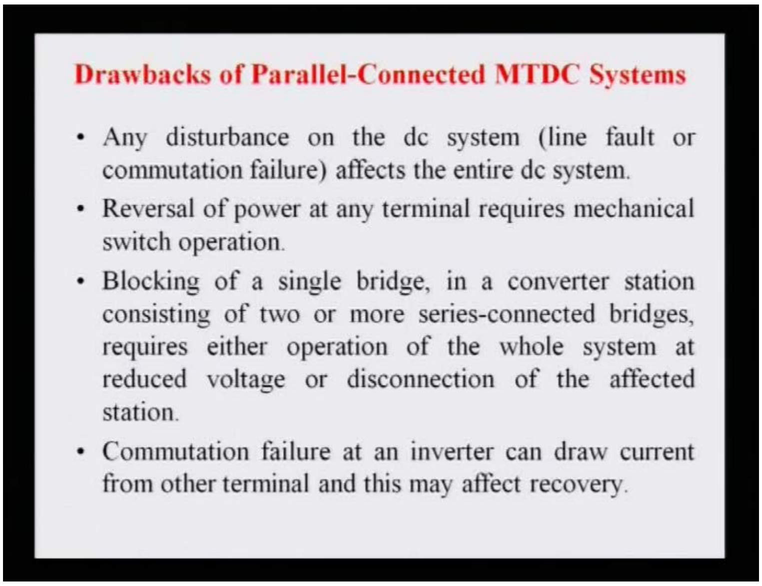

So, there is a possibility in this parallel operation, if one inverter is showing the commutation failure, so that can draw the current from the other terminal and that may affect the recovery on this system on this stable operation of the system.

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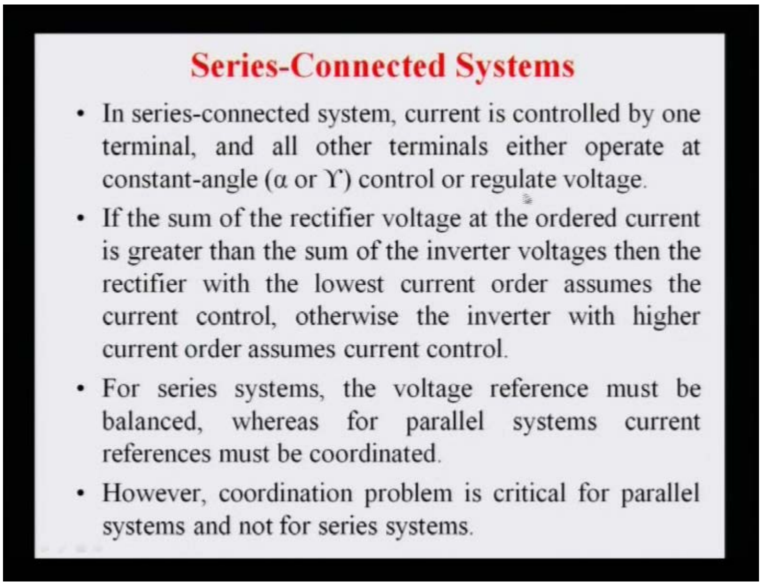

So, let us go for the second verity; that is a series connected system here as I said, in the series connected system, the current is constant and then the voltage is changed and then power is basically the controlled. In the series connected system, the current is control by one terminal and all other terminals either operate at the constant angle or gamma control or reduce or regulate voltage; means if you will see the previous case what was happening, in this parallel operation, one is controlling the voltage and others are controlling on the CC; means this is nothing but it is your CIA control and others are controlling the current, but here it is a reverse because if one is controlling CC and other is controlling basically the v, v can be your CIA or it can be your CEA; it depends upon whether rectifier or inverter. So, one is station, converter station is on constant current control and others are in the voltage or regulating the voltage. That is called here you know it is a very well, this is a constant gamma, here constant alpha, and that is why it is written here this constant angle control.

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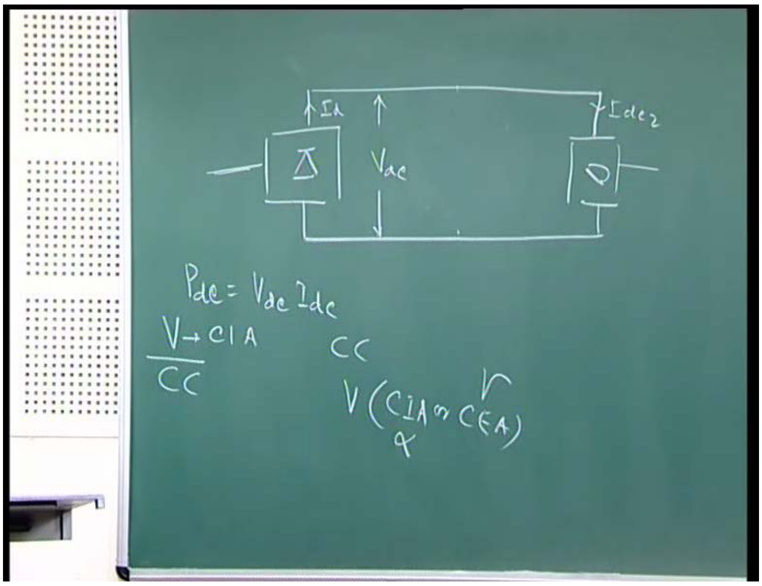

If sum of the rectifier voltage at the ordered current is greater than the sum of the inverter voltage, then the rectifier with the lowest current order assumes the current control, otherwise the inverter with the higher voltage, higher current order assumes current control. Basically this a philosophy that which one will be the constant current control; suppose you are having the variety of converters, then who will be taking this. Already I said here, the rectifier will be taking.

Here if who will be taking the constant current mode, for that it is written that if the sum of the rectifier voltage at the ordered current is greater than the sum of the inverter voltage, then the rectifier with the lowest current order assume the current control and otherwise inverter with the higher current order assume the current control. We will see the characteristic in the next slide.

For series system, the voltage reference must be balanced whereas, for parallel system, the current reference must be coordinated. Here the (( )) as I said where the parallel systems, the current reference because must be coordinate because as in the parallel I said this idc will be equal to i d c 1 plus i d c 2, and here we are talking the voltage should be because it is in the series. So, the voltage should be the balance, we have to have a close loop balance.

However the coordination problem is critical for the parallel system and it is not for the series system. Series system; the coordination is very easier in series because the voltage we are controlling, very easily we can control the voltage of each the converter terminal. Current; we are controlling and that is requiring more efforts. So, the problem is critical for the coordination in the parallel system; however, in the easy the coordination became very easy because the current is the same, only the voltage you are controlling of the entire converter. So, it is easier.

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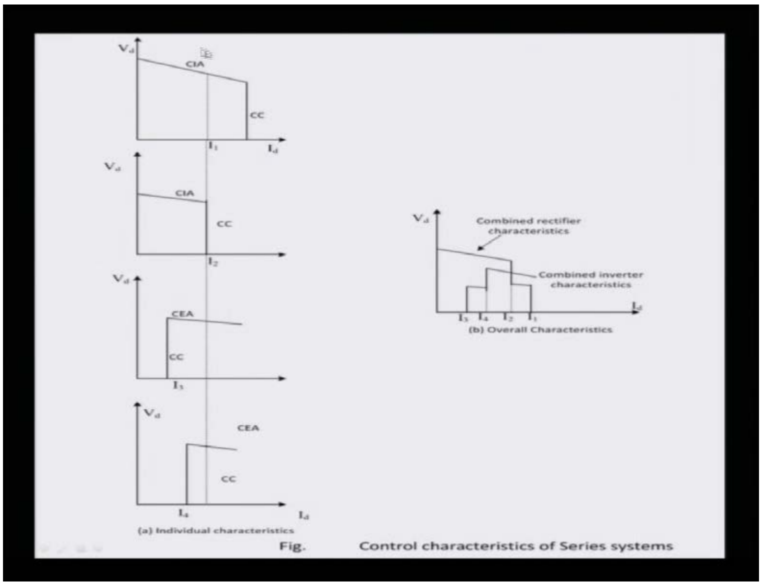

See this characteristic. This is a controller characteristic of the series system. Here it is also assumed that we are having the four converter stations. So, we are having converter 1, converter 2, converter 3 and converter 4, and the converter 1 and 2 are in the rectifier mode of operation, and the converter 3 and 4 are in the inverter mode. So, you can see here CIA and CIA plus CC, CIA plus CC that is shows that it is a rectifier, and you can see the CEA plus CC and the CEA plus CC here characteristic means these are inverters. Since we are operating at the constant current, and that is constant current you can say let suppose this is a constant current here, so, this is a constant current and then voltage is changing. Now what we can do? We can add the characteristic of the rectifier at one end and then inverter in another side; they are having the different current margin. You can see here, this is i 2, this is i 3, this is i 4, and here we are having the i 1 here. This i 1 is for basically here.

So now if you can add this two characteristic, you can find this plus at i 2 here; this is a characteristic just going here and then we are going to add this characteristic and then you can say here this we are having again.

So, basically this characteristic say, CIA plus here we are adding CC, then we are having here another slope of this characteristic, then we are going to have i 1 here. So, this is the basically the characteristic because the current here is larger. So, first we are having this characteristic, and then we are adding this characteristic. So, the combined characteristic of rectifier is this, this and then finally, here; however, this inverter characteristic; you can say i 3 is the first. So, we are having i 3 characteristic here, then we are going to add i 4 at the when i 4 is coming. So, this characteristic will be added other than this. So, here i 4 going here you can see, and this is a combined inverter characteristic.

Now, the intersection point; you can find here, we are just intersection is this. Seems that one is operating as a constant current control and that is nothing but your inverter here rectifier 2. So, i 2 is your the constant current, and others are operating on the voltage mode. They are controlling either CEA, you can see this is a controlling CEA, this is in CIA sorry, here CEA and here also CEA. So, this is your overall operation of this control characteristic of the series system. So, as I said, here one is CC, remaining on your either CIA or CEA control. In this case you can say converter rectifier 1 is on CIA control and your converter 3 and 4 on CEA control.

So, series system allows high speed reversal of power at any terminal without the need for switching operation because the id is which is the constant which is flowing; you can change the voltage very easily from rectifier to inverter, you can delay the angle finally, that will became the negative voltage and that is a reversal of power because the p is equal to i d into v d. So, i d is uni-directional, v d if you are changing that you can delay the angle the v d will change, and the finally, the reversal is very easy and; however, it is very difficult in the parallel operation because you require mechanical switch to switch over.

Also the bridges and the terminals can be taken out for the service without affecting the rest of the system because i d is a constant. So, you can take it out, you can just by pass that one and then you can maintain the i d and you can take it out without problem and then of course, you have to see the voltage in that close loop. So, it is easier compared to your parallel operations. So, already whatever the problems in the parallel operation here, you can find the series connection giving the better deal and that mean easily we can solve those problems.

The communication between the terminals is required for the controlling the line loading to minimize losses which can be achieved by relatively slow communication; here even the slow communication can do the purpose. The operation of converters in series requires the converter operation at higher firing angles, the operation of converter in the series requires the converter operation at higher firing angle and this can be minimized by the tap changing control and the backing of one of the bridge against others.

What happens here, since we are going to operate this alpha angle the CIA or CEA control where this we are just hitting its limit, we are its higher firing angle, but we can use the tapings and that tapings basically used for the minimizing this voltage this requires converter operation with higher because one which is operating the constant current here, this may having the higher angle and that can be minimized by the tapings of this one.

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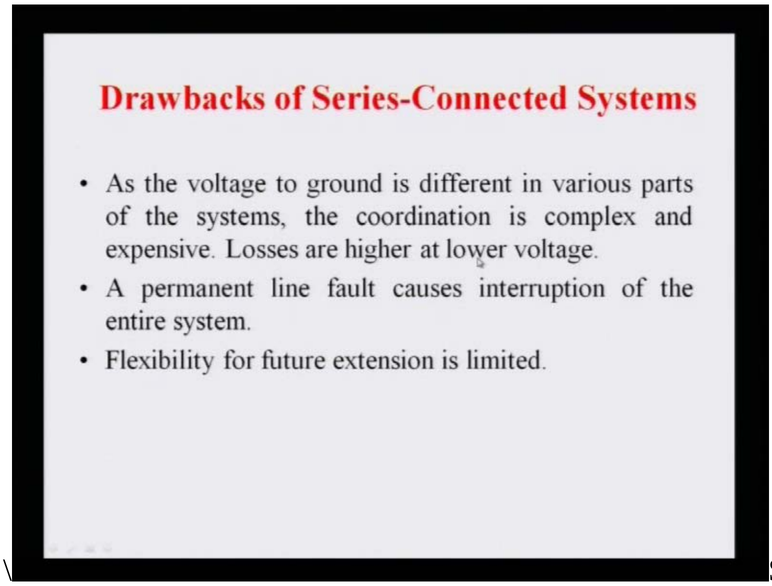

Drawbacks of the series-connected system that is as the voltage to the ground is a different in the different various part of the system, the coordination is complex and the expensive and losses are higher at the lower voltage. As I said, even the voltages are less, but the current which is flowing in the line that is i square r, i is always constant. So, it is more lossy.

Even the voltage is less or even the power is less, but still the loss is higher. So, the efficiency is one of the concern. The permanent line fault line causes interruption of the entire system if there is a line fault. So, what happen, the current is going to be short circuited and once it is short circuited, then whole system is to be stopped, and then it should be rectified; however, if there is any problem, we can very easily solve in this your parallel system.

Flexibility for the future extension is limited. It is difficult to put one converter inside because we have to change the voltage regulation, their coordination here and there; however, in the parallel operation, it is the easier.

So now with this series as well as a parallel connection, now we find that both type of configuration are having its own problem or limitations; that is, advantage as well as the merits and demerits that we find the parallel operations are still better, that is more efficient; however, it is (( )) extension is a very easier compared to this.

So, again based on your requirement that is you have to choose for the… if you are going for the multi-terminal DC transmission system whether you want the parallel or series and then you can go ahead with this. So, you have to see the limitations here as well as a parallel and then you have to decide accordingly. That is why people go for the hybrid system and that which the better option if you really go for the multi-terminal more than the 3 and 4 terminals.

The control and the protection here the most significant stress due to the multi-terminal is the increase transient and temporary over voltage in the inverters at any type of disturbance and the fault all, as all parallel converter contribute this current overshoot because if you are having some disturbance, then the transient over voltage and the transients; that is, a inverter operation is going to be difficult lead and more stressy, very heavily in the multi-terminal operation.

When the faults in a multi-terminal network is cleared by the full size HVDC breaker, switching type over voltage is introduce into the DC system; you are having the switching type over voltage; that is also one of the concern. So, these are the concern which I am talking about the protection and the control schemes. With the number of terminals or the converter operating in the parallel, the importance of the telecommunication for coordination in the multi-terminal is the increases because as I said, we have to go for more and more communication for the ultra-high voltage DC transmission system.

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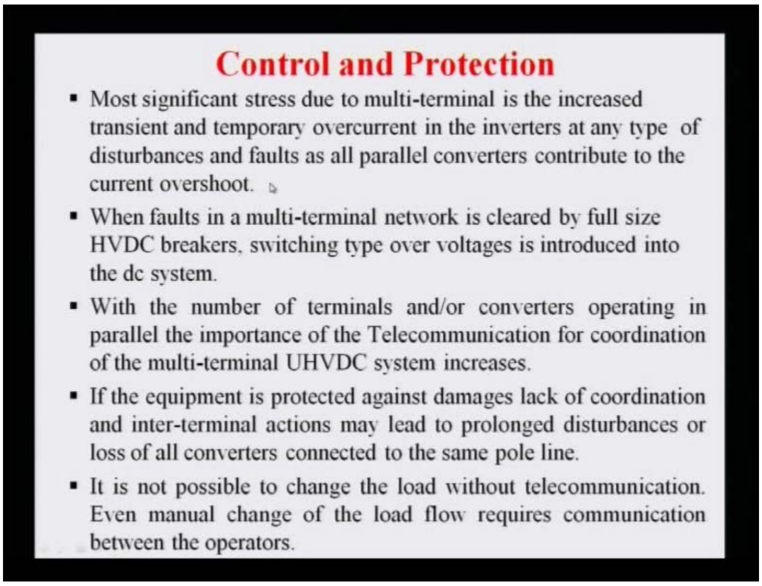

If the equipment is protected again the damage of like of coordination, inter-terminal actions may lead to the prolonged disturbances and the loss of all converters connected to the same pole lines. It is not possible to change the load without the telecommunication because if you want to change the load here, we require the communication between all this terminals. So, it is without the telecommunication or communication requirement, it is not possible. Even the manual change of the load flow requires the communication between the operations. If you want to change the power who is going to share different, then we require the control aspects and it should be communicated to each other.

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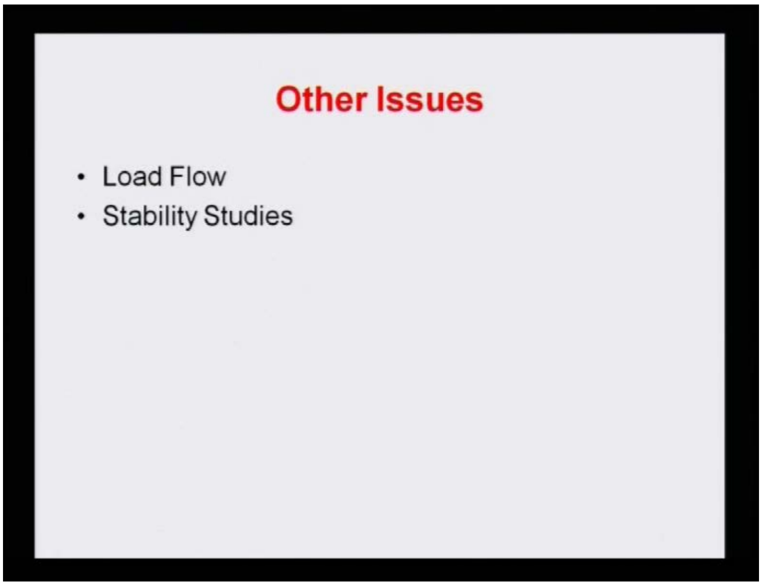

Some other issues are basically how to deal with; already we talked about the two terminal DC for the load flow and the stability studies. Now if you are having the multi-terminal cases, then you have to again solve your load flow problem. Now you have to write the governing equations for the extra terminals as well, and you have to solve the your DC equations for your the extra stations, and then along with that, you have to solve your AC DC equations.

So, the AC DC load flow, what we are going to do? We are going add some extra equations for the terminal, and then the control the DC characteristic along with the DC equations are going to increase because here as I said, if you are the parallel operation, here this one here extra you have to write here the equation for this inverter here, and this whatever the current balance equation here, the d c 1 and the d c 2 is there. So, we have to write another equation.

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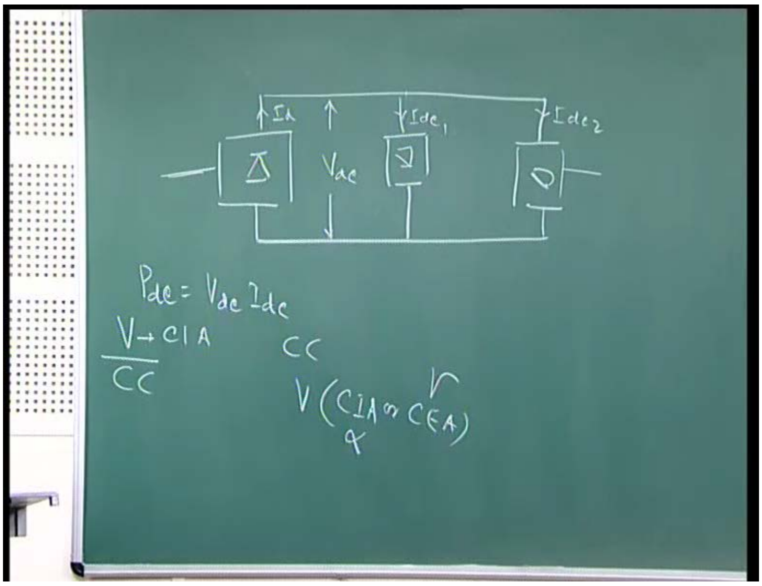

So, you have to add the DC equation for this, another some extra governing equations that should be used in the DC part and then finally, you have to form AC DC equation, whether you are going for the sequential or you are going for the elimination variable method or unified methods, then you have to eliminate those variables and you have to solve, and then you can go for the load flow.

Similarly, if you are going for the stability studies as well, in the stability studies, you have to write this DC equations, whether you are taking at the simple model or you are going for the detail or response model, accordingly we have to write the control aspect, control characteristic of the extra terminal that will be also used, and then if you are going for the transient stability, then you have to solve the differential equation corresponding to those terminals, and also if you are going for the steady state or dynamic stability or small signal stability, then you have to write the lionized equation corresponding to extra terminal, and then you have to see there is eigen values and analyse and then you can find the system stability.

So, simply if you are adding more and more converters, you have to write more and more governing equations, then you can use in your systems, in your methods whatever you are existing; one like the two terminal cases, you have to add it. So, since we are talking here the one diverse topic; there is multi-terminal, already we discuss much detail about the two terminal HVDC system for both load flow and the stability studies that should be incorporated because here I discuss only the control aspects, but the load flow and the stability studies; whatever the extra terminals you are having, you have to write the governing equations accordingly, and you have to incorporate in your… Whether it is load flow, then you are on the load flow or if you are going for the stability studies, you have to incorporate there.

So, with this, I am going to conclude; that is, in this lecture, I just discussed the multi-terminal HVDC system because if you are having the two terminals, there are certain limitations that can be solved by this multi-terminal HVDC system and the more advancement if you are going for HVDC; HVDC based on the IGBT and that will solve the lot of problems, and then you can go for the multi-terminal DC systems as well which gives more flexibility and it will offers more advantage; that is, a point to point transmission is no more valid and you can go for more tapings over power.

So, this ends the lecture number 1 of this module 7, and in this next lecture, we will discuss about the HVDC light or HVDC plus, and that will be discussed in the next lecture. Thank you.