High Power Multilevel Converters - Analysis, Design and Operational Issues
Dr. Anandarup Das
Department of Electrical Engineering
Indian Institute of Technology, Delhi

Lecture – 37
A Case Study on MMC and CHB

In this lecture we will talk about the Case Study on MMC and CHB, we will take two small examples and we will design the MMC and the CHB converters. So, let us first start with an MMC for an HVDC application.

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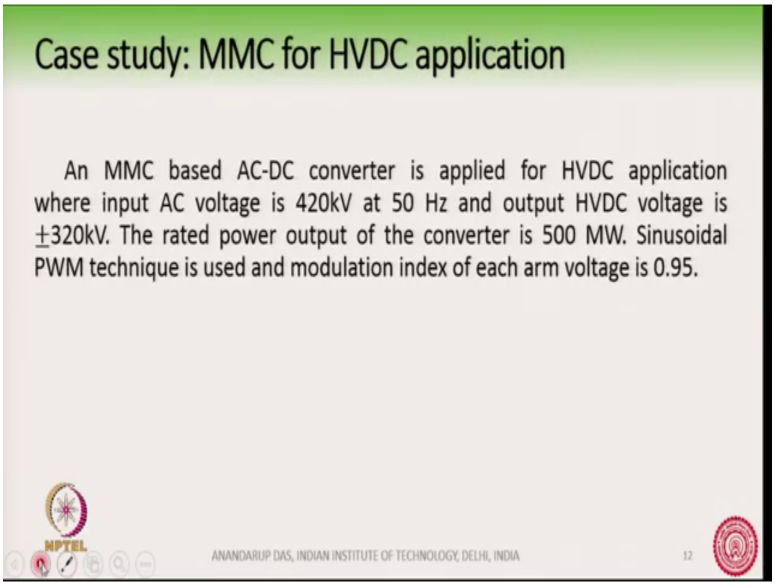

So, an MMC based AC to DC converter for example, so is used to be used for an HVDC application where the input AC voltage is 420 kV line at 50 Hertz and output HVDC voltage is plus minus 320 kV ok. The rated power output of the converter is 500 mega Watt and the modulation index of each arm is 0.95 ok.

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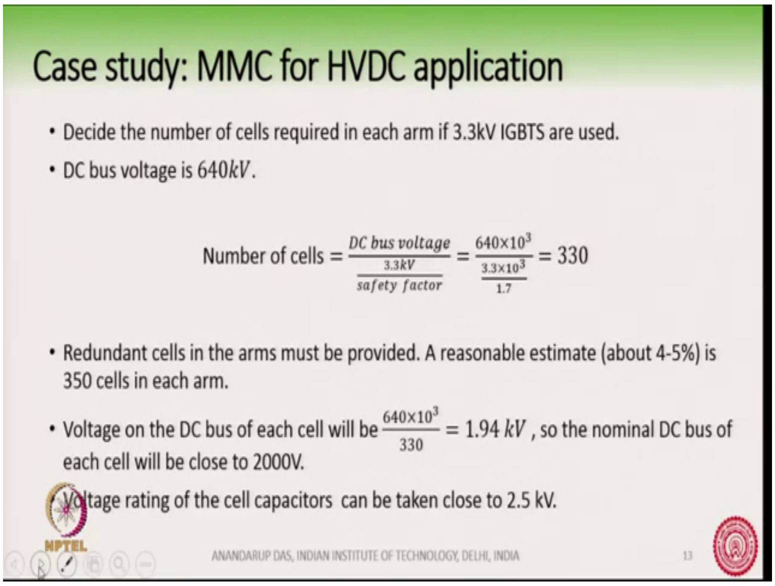

So, let us see how we can design the different components. So, first we decide on the number of cells required and suppose we choose that there are 3.3 kilo volt IGBTS, we will use ok. Now, this again depends on experience like whether you will go with a 3.3 kV IGBT or whether you will go with a 4.5 kV IGBT.

So, let us see how this 3.3 kV IGBT is if we use how does the design go ahead. Now, the DC bus voltage is around 640 kV, so the number of cells we can choose as the DC bus voltage divided by 3.3 kV by safety factor which gives us a number of about 330 IGBTS to be used in e. So, 330 number of cells ok, if we use 3.3 kV IGBTs.

So, if there are 330 number of cells we have taken a safety factor of about 1.7; that means. So, we have taken a safety factor of 1.7 here in this equation. Now, redundant cells must be provided in the arms, so a reasonable estimate can be something like 4 to 5 percent right. So, we can choose like about 350 cells in each arm of the MMC, this can be a starting point in your design right.

Now, if we have 350 cells in each arm we have about three means some of them are redundant cells. So, that will be like they will be shut off during the normal operation ok. So, like they will be. So, only 330 cells will be used at any point of time right, but the rest cells can be like cold standby ok. So, voltage on the DC bus of each cell if we use 330 cells the voltage on each cell will be 640 divided by 330, so 1.94 kV.

So, the nominal DC bus voltage on each cell will be close to 2000 volts right. So, we are using 3.3 kV IGBT for a DC bus of 2000 volts ok. So, we are taking almost a safety factor of like 1.6 or 1.7 close to that value which is kind of like a reasonable approximation for the first estimate ok. So, the nominal DC bus will be like around 2000 volt.

So, based on that the voltage rating of the cell capacitors can be taken close to like 2.5 kV. So, we keep some margin because there will be a ripple on the 2000 volt and if I take like 5 percent, if I take about 10 percent ripple. So, this 2000 volt can go to 2200 volt. So, I can take a rating of the cell capacitors may be 2.5, maybe someone may take a little bit less or more, so that can be taken. And then what is the current rating of each device?

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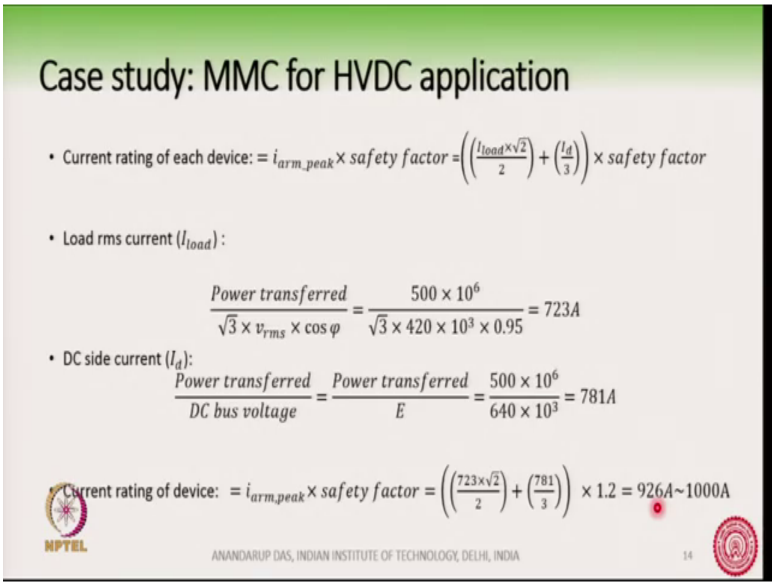

Now, current rating is this i arm peak peak current through the device into a safety factor. So, what is the peak current through the MMC each arm? And that is equal to half of the load current into root 2, half of the load current i rms this is the rms load current half of that into root 2 plus the one third of the DC current that much of current is flowing in the peak in the arm. So, and then again we have a safety factor.

So, how much is the load rms current? So, if we are transferring power of 500 mega Watt, then we can use this formula here and when get about 723 ampere ok. So, we can say like 750 ampere of current will is the load current. And what is the DC side current? DC side current is power transferred by E and the power transferred is this much and the E is this much. So, 781 ampere is the DC side current.

So, therefore, the current rating of the device if you take like this and take a safety factor of 1.2 you get that the current rating of the device is 926 ampere peak and so you may choose a device of about 1000 ampere IC; IC rating of the IGBT you can choose about 1000 ampere, close to that value ok.

So, this will ensure again we have to be careful like what is the how much is the I squared t rating of that device during that 10 micro second that must be kept in mind. Now, next one will be like deciding the cell capacitance right.

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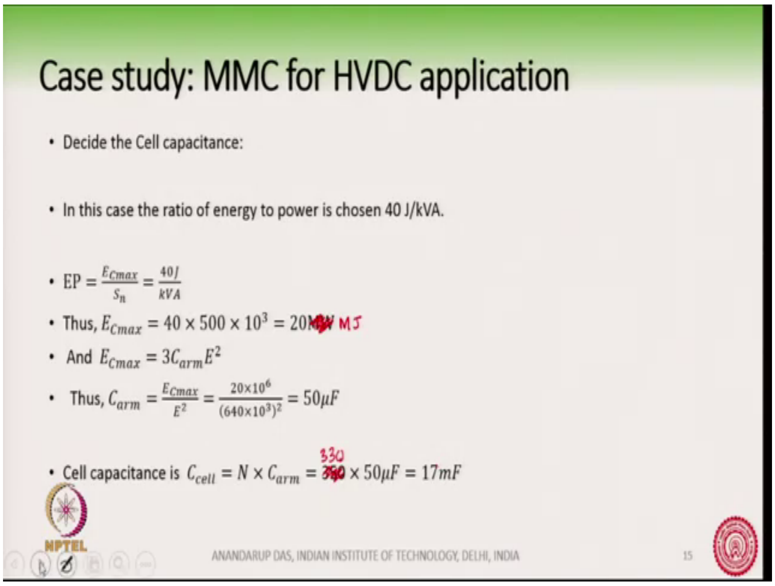

Now, suppose we choose a EP value of 40 J per kV A energy to power that ratio. So, therefore, E Cmax the kV a is 500, so E Cmax is 400 into sorry 40 into 500. So, 20 mega Watt that much of value sorry this is mega Joule not mega Watt, so there is mistake here; so this is 20 mega Joule ok. And E Cmax as we have seen earlier is 3 times C arm into E square and so C arm will be equal to E Cmax by E square and will come out to be 50 micro Farad that is this value 50 micro Farad is the total arm capacitance effective arm capacitance right is equal to 50 micro Farad.

So, the cell capacitance is related to the arm capacitance by this because there are N number of cells or N number of capacitors connected in series right. So, therefore, C cell is N times the C arm and so if there are 350 number of cells anyway this should we have been. So, there are 330 number of cells; 330 number of cells and we have 50 micro Farad. So, a value of roughly 16 mill Farad will come; 16 around 16 to 17 milli Farad of cell capacitance will be required ok.

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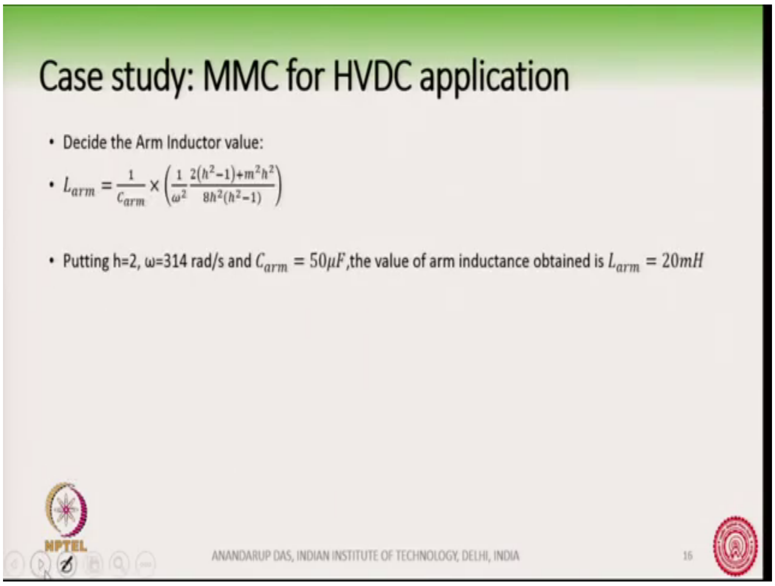

Again once we have decided this arm capacitance, then we decide the arm inductor value ok; arm inductor value and arm inductor value will be can be obtained from this formula here. So, if you put h equal to 2 and omega 314 and C arm as 50 micro Farad, the value of the arm inductance is about 20 milli Henry ok.

So, this is how we design the arm inductance, we design the cell capacitance, we design the IGBT or we can choose the devices, we have to also choose the diodes along with that and the thyristors we can also choose which can tolerate the fault condition. Now, I should first say that this kind of a design is not possible in such a short span of time, it requires a dedicated team of engineers and having expertise for many years working together for several months or years to develop such converters.

Anyway in this short span I will just briefly say what are the basic design ideas that we should keep in mind. Remember we are only talking here about the electrical aspect and in a practical design you will have many other aspects like electrical, mechanical, thermal all these have to be incorporated. We will not go into the other aspects, but we will mostly focus on the electrical part of the converter.

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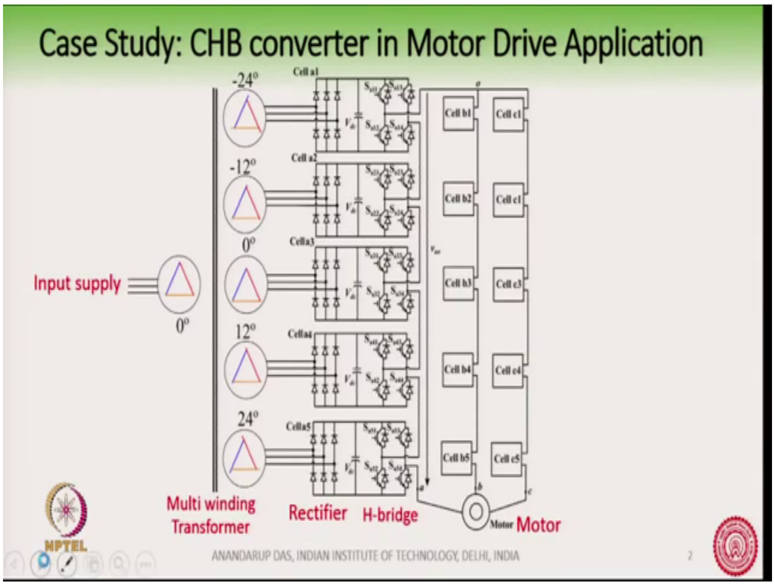

So, we have seen this earlier. So, for example, this is the structure of a cascaded H bridge converter in which you can see that there are say 5 or 6 cells. So, this diagram is shown with 5 cells here and this is the input supply and then there is an extended delta multi winding transformer. And each secondary is connected to a 3 phase diode bridge rectifier which forms the DC link and then you have the H bridge here which are then connect connected in cascade and feeds a motor ok. So, very briefly we will see how we can choose components electrical components in this diagram.

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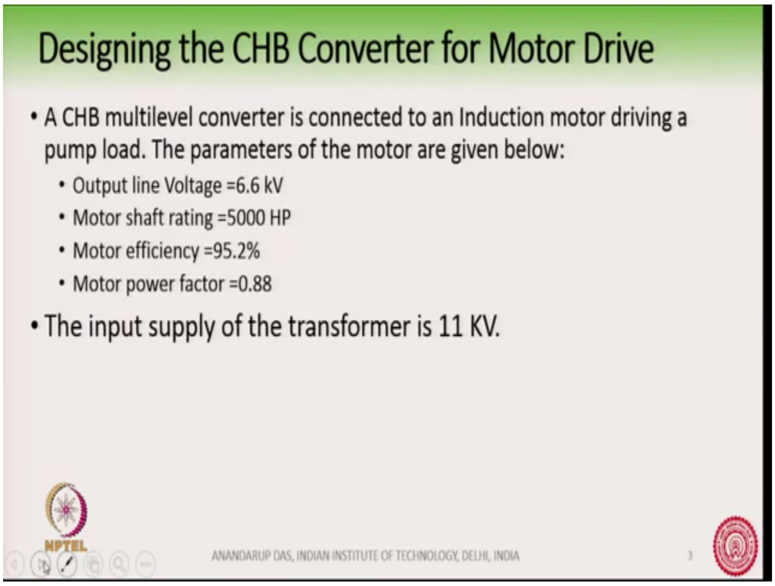

So, for example, we have a CHB multilevel converter which is connected to an induction motor driving a pump load. Most of the cases induction motors in the industry are used for driving pumps, compressors, fans etcetera many of them. And another very big application area is the drives application I mean the motors which are used for say tractions something like this.

So, there is a slight difference between these two applications because in such drives where you suppose if you have a pump type of drive, then the load torque is proportional to omega squared. Whereas, in suppose if you are using an induction motor for a traction drive then the load torque often is independent of the speed. So, the torque requirement and hence the current required from the converter that will change.

In case of pumps you will require a very less torque at low speed whereas, in case of a traction drive you may need the full torque right at or very close to 0 speed, so there is a difference. Anyway in this application we are considering a pump load and so the parameters of the motor are given as something like 6.6 kV and 5000 HP with an efficiency of 95 percent, 95.2 percent and the motor power factor is 0.88 and the input supply to the transformer is 11 kV. So, these are some of the data given. So, we can make a quick the first thing is to find out the converter rating.

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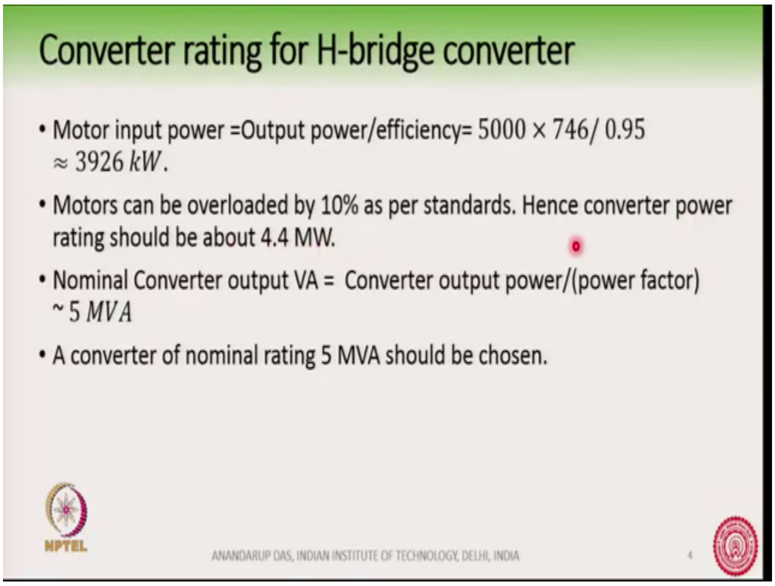

So, how can we know the converter rating? So, the motor input power is 5000 HP, so and we divide by the efficiency which is taken as about 95 percent. So, we see that the motor input power is something very close to 4000 kilo Watt ok. Now often these motors are can be overloaded by 10 percent.

So, there are several standards which say for example, a Nema standard they say that the motors should perform as means with the full specification if it is if the load torque is 10 percent over the nominal torque. So, this is often stated. So, in our converter design we can say that the converter is going to be able to supply the motor with 10 percent overload when the motor is 10 percent overload.

So, we can choose the converter power rating to be about 4.4 mega Watt ok. In this is something which can also vary from design to design ok, we are taking very I means with sufficient margin in our design ok. So, the converter power rating should be 4.4 mega Watt because why I said that there can be sufficient. So, when you say overload, then another question may come up is like for how much duration of overload, is this 10 percent for 1 minute or is this 10 percent overload for continuous operation?

So, they mean generally it is not continuous it is a short term overload rating, but again so this will vary from application to application. But we are not going into so much of details of the direct application and we are doing a simplistic analysis here again I told you we cannot cover such a design in such a short span of time. It will required different types of analysis and also what are the worst case conditions that this design has to withstand all these factors have to be taken care of.

Now, we can choose like an initial guess that the converter power rating should be 4.4 mega Watt. So, the converter output VA will be, so converter output power 4.4 mega Watt divided by the power factor and so this will be about 5 MVA ok. So, a 5 MVA converter can be chosen to drive such an induction motor, 5 MVA power.

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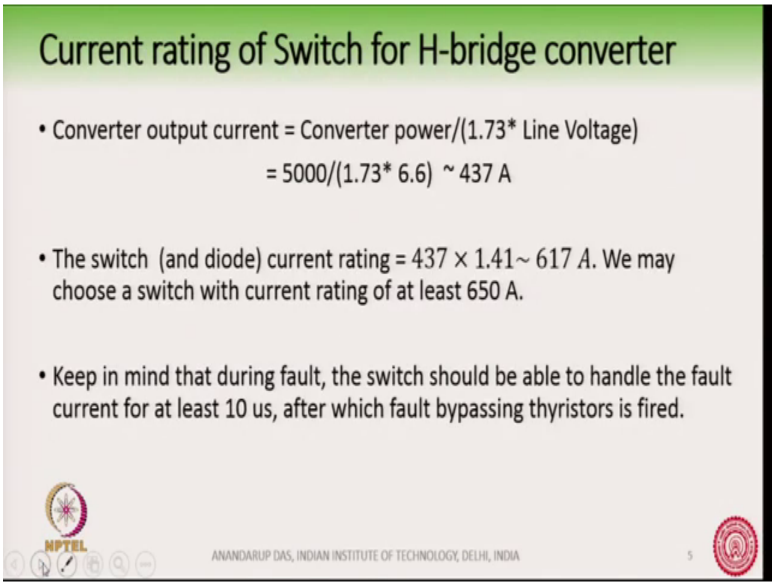

So, what is the converter output current?. So, the converter rated voltage is 6.6 kV and 5 MVA. So, about 437 ampere that is the rated output current of the converter. So, all the switch and diode should be rated for at least 437 into 1.41 that is the this value is the rms current and so the peak value is about 617 ampere. So, all the switches and diode should be rated for at least this value ok.

So, for the safety purpose we may choose a switch with a current rating of at least 650 ampere someone may choose even 700 amperes also ok. So, this is kind of like how much margin you can keep in your design. Now, but when you take such a switch a diode or a IGBT you should always see the I square t rating of such a switch, it is very important to note that during the fault the switch should be able to handle the fault current for at least 10 microseconds or even more ok.

So, the total energy that is the I square t during this time may be 10 microseconds sometimes going up to 15 micro second because 10 micro second is the time before after which the IGBTs will be shut down ok, the diodes can continue more much more than 10 micro second, but IGBTs we have to be careful. So, that it should have an I square t rating which can sustain the maximum fault current for that much of time that is 10 micro second or maybe 15 micro second ok. So, we have to when you choose the IGBT you should look into the I square t rating of that.

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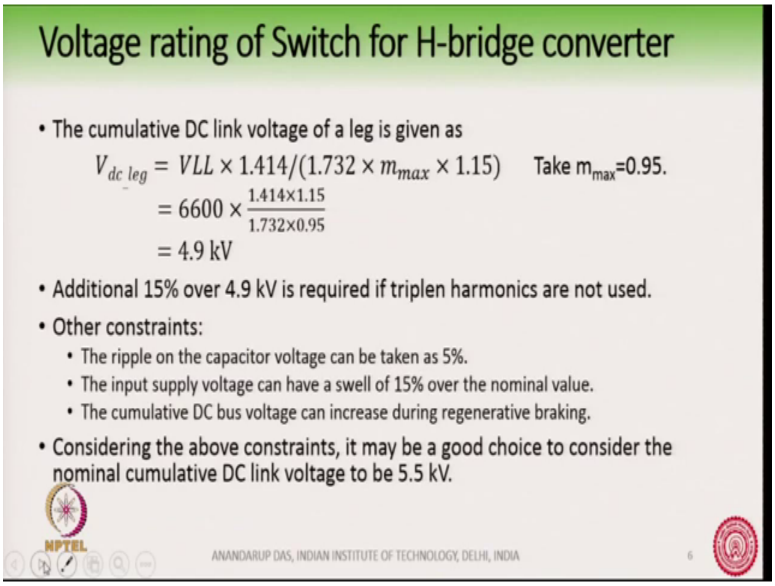

Now, once we have decided on the current rating of the switches, then we look at the voltage rating of the switches. So, the cumulative DC link voltage of the converter how much is the cumulative DC link voltage, what is cumulative DC link voltage? That is the sum of the DC link voltages of all the cells taken together ok.

So, that is the cumulative DC link voltage. So and this, so this we are terming we are giving a term V dc leg this is the cumulative voltage and that is the line voltage times the peak value of the line voltage divided by root 3. So, as to get the phase voltage and m max into 1.15 ok; m max is the maximum modulation index and 1.15 is coming because we are using a third harmonic or a space vector pwm modulation technique.

So, the value of m max can be taken as 0.95 again some user may take it 0.97, 0.98 something like that, but we have kept it 0.95. So, V dc leg cumulative DC link voltage is about 4.9 kV. If we do not use the third harmonic or the triplen harmonics, then we will need additional 5 15 percent over 4.9 kV that is 4.9 into 1.15 will be needed if you do not use the triplen harmonics, if we just use sinusoidal pwm ok.

So, this is the total DC link voltage, the DC link voltage of or the sum of the DC link voltage of all the cells together, but there is also want some other constraints like the ripple on the capacitor voltage can be taken as 5 percent. So, there is always a ripple and this ripple is primarily coming from the fundamental frequency at the input. So, there is of ripple which is can be taken as 5 percent.

And the input supply voltage, yes this is also important input supply voltage can have a swell of 15 percent over the nominal value. So, this is sometimes important because such 11 kilo volt lines sometimes have input surge voltages. Now, this cascaded H bridge converter has uncontrolled rectifier at the input. So, if there is a surge voltage at the 11 kV line, then what can happen is this surge voltage will directly come on the DC link of the H bridge.

So, the input supply can also have 15 percent and also we have to note that the cumulative DC bus voltage can increase during regenerative braking also. Why? Because when the motor is regenerating suppose you are breaking the motor and it is feeding back the energy it will come to the DC link and the DC link voltage will go on increasing. Because the diode rectifier does not allow the voltage to go back I mean not the voltage the diode rectifier will not allow the energy flow from the DC link into the AC side, its an unidirectional device.

So, therefore, if there is a regenerative braking; that means, the energy is coming from the motor it will be dumped inside the DC link voltage and so the DC link voltage will increase in magnitude ok. So, often we see that in such CHB or in such diode bridge rectifiers we have a additional chopper on the DC link and this additional chopper fires once the DC link voltage goes above a certain predefined magnitude.

Say if the DC link voltage goes beyond 20 to 30 percent of the nominal value then the chopper is fired because otherwise it will destroy the switches in the which are connected to the DC link and a part of the H bridge ok. So, if you see the above constraints then we can say that it may be a good choice or it may be a starting point or it may be a starting choice to consider that the nominal DC link voltage is about 5.5 kV ok.

So, I am taking about 10 percent more than this value. So, 5.5 kV is the cumulative DC link voltage.

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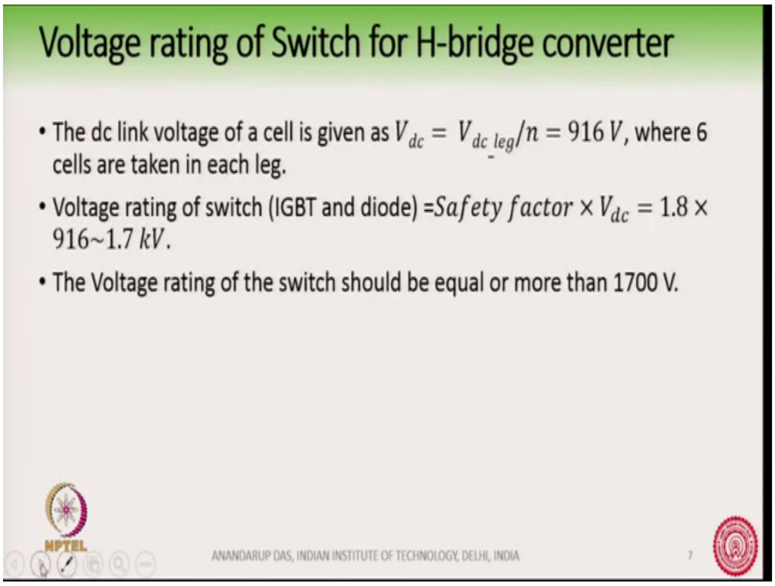

And the individual cells suppose we take 6 cells in each leg. So, the cell voltage is therefore, this 5.5 kV divided by 6 that is about 916 volt the DC link voltage. So, voltage rating of the switch can be taken as a safety factor into V dc.

And if you take a safety factor of 1.8, then we see that the devices are about 1700 volt IGBTs and diodes ok. So, 1700 volt IGBT or diodes are quite frequently available at this power at the voltage and at the current rating which we have talked about. Now, why did I choose 1.8 as the safety factor? Now, this is again depends on the designer.

As I told you this DC link voltage will vary during the operation of the converter, but I will also say that the DC link voltage. So, when you run such a converter there may be several types of possibilities while running this converter often you will see for example, this converter is used for a long cable application.

Now, when you have a long cable application it may happen that there will be voltage reflection because the cable and because the inverter and the or the converter and the motor may be far away from each other ok, in a long cable suppose in a mining application. Then what will happen is there will be voltage reflection from the motor generally that is less in multilevel converters, but still voltage reflection is something which user should be aware of or a designer should be aware of. And so because of that voltage reflection you would like to keep some margin on the DC bus ok.

So, this is one reason why we have kept 1.8 and also momentarily for example, you have a bypassing happening in the DC link. And during the process of bypassing or during the process where the IGBTs are getting shut off you may find that the DC link voltages are temporarily increasing, I mean the devices are subjected to a voltage of more than the rated voltage of 916 volt.

So, for these reasons this safety factor of 1.8 has been taken, many designers suppose you are working in a harsh environment many designers will take a safety factor of maybe 2 maybe even more in it. So, we are just giving you a starting point for the design ok. So, the voltage rating of the switch we have taken like similar to 1000 and 17 sorry 1700 volt.

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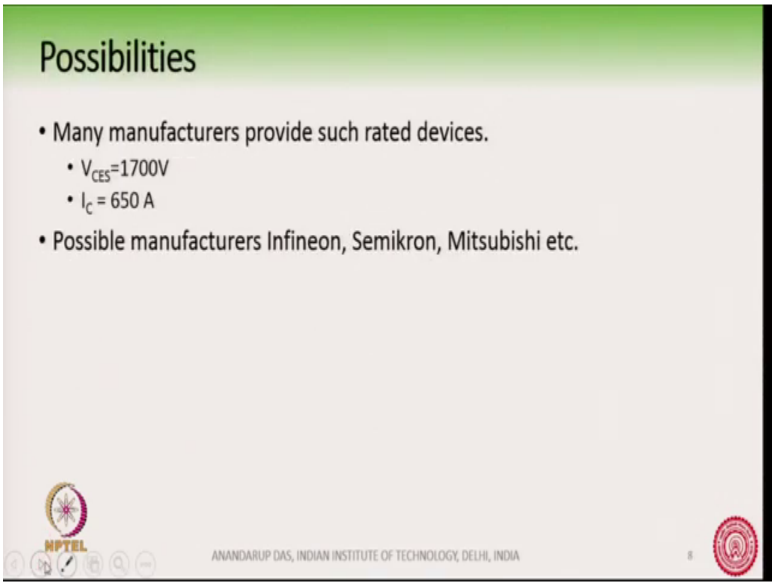

So, for this rating of 1700 volt and 650 ampere you find if you go to the websites you find there are several manufacturers like Infineon, Semikron, Mitsubishi (Refer Time: 27:07) many other manufacturers are there. So, you can go to their websites and you will find these kind of switches, you can see their properties the datasheet of these switches and can see and can also see their application notes and you will find a lot of information how to use those switches.

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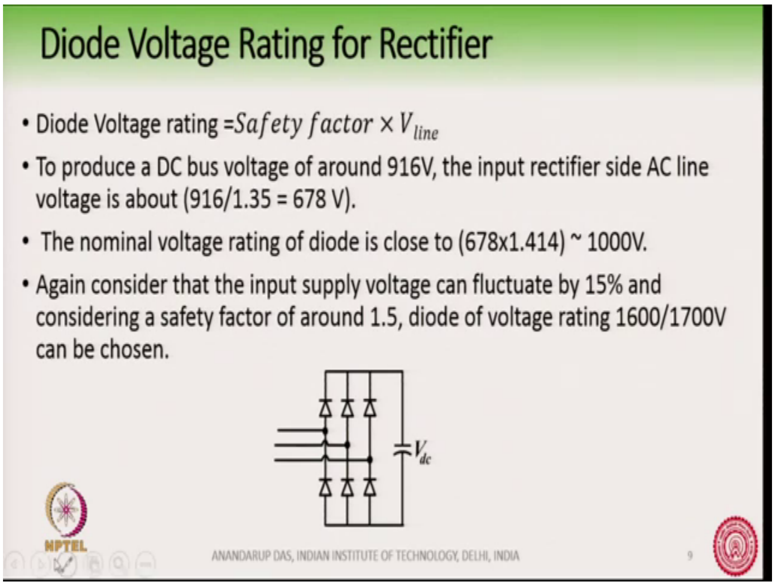

Now, the other thing is the diode voltage rating for the rectifiers. So, we are now thinking about the input side diode bridge rectifier ok, again the diode voltage rating is the safety factor into the line voltage ok. Now, if you want to produce a DC bus about 916 volt the input rectifier side AC line voltage is about 678 volt rms because the DC bus voltage with such a rectifiers is about 1.35 times the AC rms line voltage.

This information you can see in any power electronics textbook, the rectifier section and you will find this information that it is about 1.35 times, so we are not going into that details. Now, so the nominal voltage rating of the diode is close to about 1000 volt, again the considering all these safety factors into account our diode of about 1600 or 1700 volt these kind of a diode can be chosen, the voltage rating of the diode.

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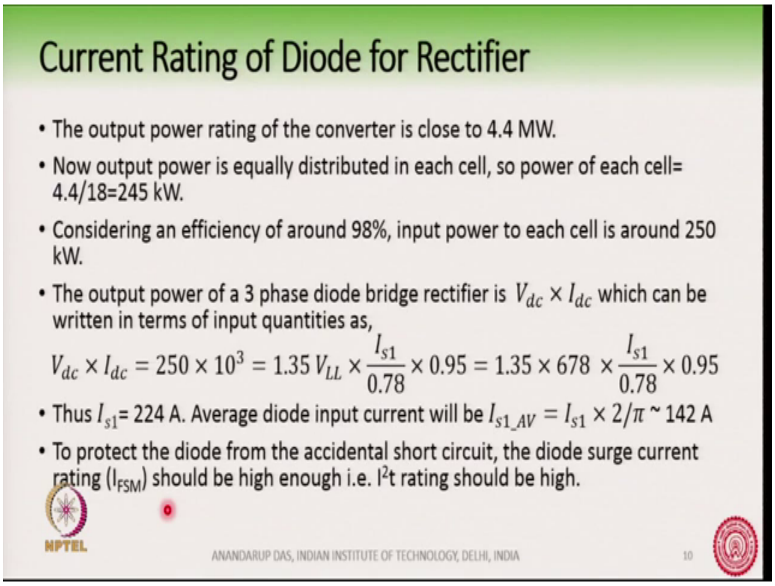

And then we can also see what is the current rating of the diode for the rectifier. So, the output power rating of the converter is like close to 4.4 mega Watt. So, the output power is equally distributed in each cell we are assuming its getting quality distributed. So, the power of each cell is about 245 kilo Watt, so this is the.

So, there are 18 power cells because there are 6 power cells in each leg and there are 3 phases. So, we have 18 power cells. So, the each cell handles a power of about 245 kilo Watt. So, if the efficiency of the power cell is about 98 percent, so the input power to the each cell is about 250 kilo Watt ok. Now, the output power of the rectifier is equal to V dc into I dc which you can again write in terms of the input quantities as V dc into I dc is equal to this is the 250 kilo Watt, this is the output power.

Then input sorry this is the input power of each cell V dc into I dcs 250 into 10 to the power 3 and which is again equal to 1.35 V LL into I s 1 by 0.78 into 0.95. How do we get this one? Again we get this factor from the analysis of 3 phase rectifiers the fundamental source current is 0.78 times the DC current you can see this one in any or electronics book the rectifier section and the DPF is like 0.95, Displacement Power Factor is 0.95.

So, by substituting these values here we get that the input side fundamental input current is about 224 ampere and the average diode input current will be 2 by pi times this I s 1 that is about 142 ampere. So, this is the I F average the average diode current 142 ampere this is what is given in the data sheet of diode rectifiers and accordingly you can choose which diode to use.

Again the diodes have to bear the short circuit current accidental short circuit current and the diode surge current I FSM should be high enough ok, again I FSM of diodes are very high. So, diodes and thyristors both have this surge current rating very very high as compared to for example, IGBTs. So, this is something which favours the diodes and rectifier class of diodes have been used frequently because they can sustain the short circuit current. So, remember this I square t rating also you should check.

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And then with this V RRM and I D of this one you can see many manufacturers 1600 volt and 150 ampere rating. So, Semikron, Mitsubishi, IGBT sorry Infineon and other manufacturers ST and there are many other manufacturers you can just have a look into the websites.

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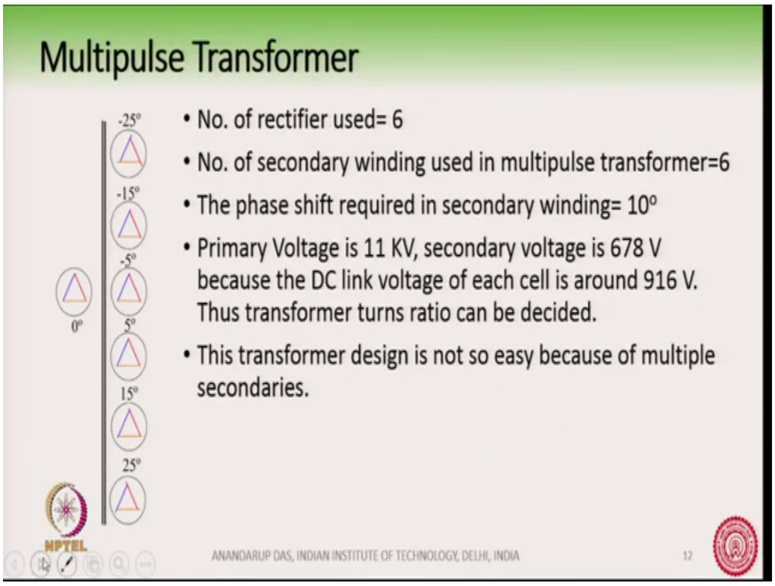

And what about the multiples transformer? Multiple transformer number of rectifiers to be used is 6 there are 6. So, there are 6 secondary windings is 6. The phase shift required in the secondary windings is 10 degrees which we have covered earlier also. The primary voltage is 11 KV, secondary voltage is 678 voltage because the DC link of each cell is around 916 volt. So, then you can decide what is the transformer turns ratio. So, the primary is 11 KV line to line and secondary 678 volt line to line.

So, you can now decide what is the value of N 1 is to N 2. However, this transformer design is not so easy, its quite a complicated transformer with 1 primary and 6 secondaries also these 6 secondaries are connected in extended delta. And it will take time I mean this transformer designing is complicated and also there are several tests. So, this is not a standard transformer and several tests have to be performed on this transformer.

So, as to get the accurate say how much is the input current cancellation how much are the forces on the transformer during short circuit there are many tests which has to be performed on these transformer ok. So, its an elaborate arrangement here.

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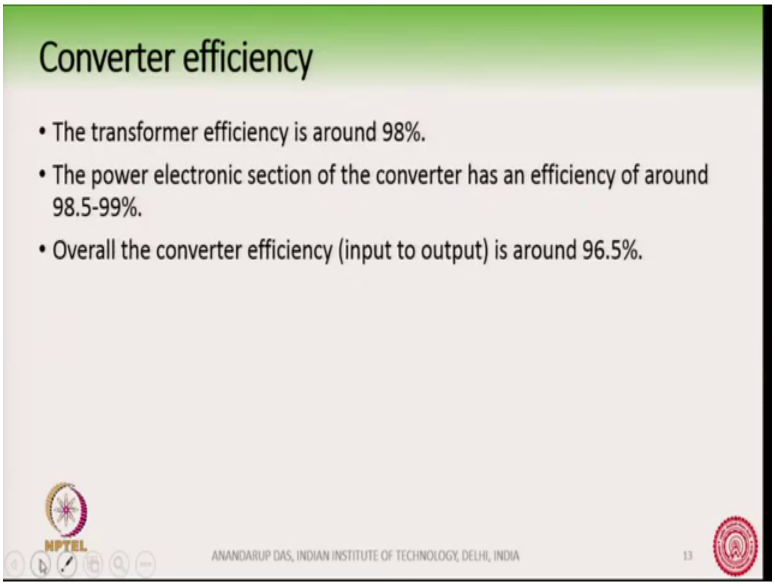

And coming to the efficiency, what is the efficiency? The transformer efficiency is close to about 98 percent. Again this is very rough approximation and then the power electronics section of the converter has an efficiency of about 98 to 99 percent of efficiency. So, the overall the converter efficiency input to output like from the transformer primary and going to the motor the overall converted efficiency is more than 96 percent ok.

So, this is what generally the cascade H bridge converters they are operating in this efficiency range ok. In spite of; in spite of having so many components and in spite of having such an elaborate transformer and so many devices working together it is actually surprising to note that the efficiency is quite high in fact. And one of the reasons as I told you before also one of the reasons why the efficiency should be high is that they are processing a large amount of power.

So, even this 3 or 4 percent of loss is substantial loss which will appear as heat inside the converter and has to be dissipated out. So, the efficiency of such multilevel converters like cascaded H bridge may be 97 percent or something like that MMC for HVDC application they are having an efficiency of more than 99 percent ok. So, these are some of the range of efficiency which we encounter in such multilevel converters.

So, this then forms this is again as I told you this is a very basic guideline and may be just a starting point of your design, but much more analysis needs to be done on this lot of analysis design, iterations and then again lot of testing has to be done. So, it will take a long time to with a dedicated team to perform the whole design fabricate it and then run the converter. So, I have just given you a basic starting point as part of the course here.