High Power Multilevel Converters – Analysis, Design and Operational Issues
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Lecture - 25
Design of Components in MMC

So, this part is an announcement for the TAs, like we are recording now for MMC, the one part that the design of components. So, this part what I am recording now will get included in or will be cut and paste into the MMC original series of lectures.

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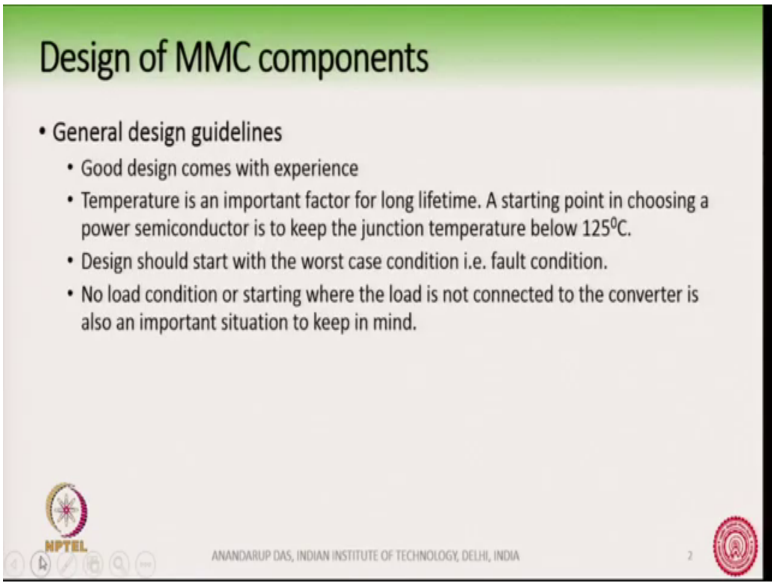

So, today we will see the Design of MMC components ok. Now, this subject of design is very tricky and challenging subject ok. It is not so easy, definitely it is not so easy and that too with something like MMC having hundreds of cells and such a big convertor handling maybe hundreds of megawatts to gigawatt of power.

So. in fact, I can say that whole course can be taken just how to design MMC components ok. So, what we are going to cover is a very preliminary introduction based on whatever we have studied and whatever equations we have derived; based on that a very rough estimate ok. That is what we are going to cover. Because this is a huge subject and it is also true that like dedicated teams of engineers and researchers they work in a group and they try to find out how to design these components so, it is a big task.

Anyway, we will just briefly highlight the salient features or the process of designing these components. Now before we go into the MMC design, there are some general very general design thumb rules ok. The first thing is good design comes with experience. Absolutely no doubt about this fact that often good designers are experienced people who have been in the industry for many many years.

Why experience matters is primarily, because in particular for such hardware based components or with such electronic components; the experience comes from getting information from large field data. For example, if you choose an IGBT, how that IGBT in the history has performed. How was it performance, how much how many times it has endured the fault condition and like those things. So, it all comes with this experience.

So, to be a good designer, one has to encounter a lot of situations, difficult situations makes a good designer and then you have to kind of solve those problems and get a very good understanding. Of course, nevertheless I will also say that often new ideas come from also young engineers and young people, fresh new ideas are always welcome. Now when you design a system then it is very important that you take care of the temperature.

Temperatures are very important for long lifetime operation of the converter equipment. So, we generally follow the Arrhenius rule, when you are in the industry which is it is also it is not very much mathematical, but it is kind of like a general thumb rule that every 10 degree centigrade rise in temperature will reduce the lifetime of a component or a converter by half ok.

This is a very basic thumb rule, but it works quite well. I mean; so, when you are working with converters temperature is something which you should be careful of ok. That is why we have elaborate arrangements for heat sinks as well as for taking out the heat from the heat sink through water channels and like that. So, when you talk about these IGBT s or converters, those are kind of like important components which have high temperature.

So, it is a good idea to keep the top junction temperature below 125 degree centigrade for silicon based IGBT s. It is a good idea or a starting point it can go a little bit higher also, but it is starting point can be like we keep it 125 degrees. Then another very important factor to be taken care of is the fault condition. In fact, this I think is the point from which the design should start

You see the worst condition to which this converter is subjected to and then you start the design from there. The reason for this is; when you want to build a very robust system. So, when you say the robust the system is robust it means that under the severe stressed condition also it will perform or it will protect itself from the most severe condition of operation. And what is a severe condition of operation? It is the fault condition, short circuit fault for example, that is a very severe condition on the converter.

A huge current is flowing and tremendous heat generation is happening and then you have to protect your converter in spite of all these severe condition. So, you have a good designer always identifies what are the worst guests worst case situations which the convertor is subjected to and accordingly you should start your design.

So, this is something which must be kept in mind and from that severe most severe condition you come to the rated condition of the operation of the converter. In that rated condition you try to optimize the efficiency ok. What is the maximum efficiency I can get during or close to the rated condition of operation.

If you can extend the range of efficiency from that rated condition to no load the whole range of operation if you can maintain a very good efficiency that is a very good achievement often, we do not get the same value of efficiency from no load to full load. So, we then choose that ok, the efficiency should be highest near to the rated operation of the converter ok.

No load condition is also something which is something to be kept in mind because in a no load condition the load has been thrown off the converter. So, how the converter will behave in the absence of a load is also something to be is an important factor to be kept in mind also apart from no load I should also include that the starting operation of the converter.

How will you start the converter? Because the converter is de energized it is dead and then you start energizing the converter. For example, in MMC also we have something called as pre charging of the capacitors. So, we pre charge the capacitors to a particular voltage after which we start the operation of the converter. So, these are some of the basic guidelines to keep in mind.

Now, here we will briefly, very briefly we will touch the electrical how to design the electrical parameters in MMC. So, MMC is mostly nowadays still used in HVDC transmission and these are the some of the voltage levels which we use in MMC.

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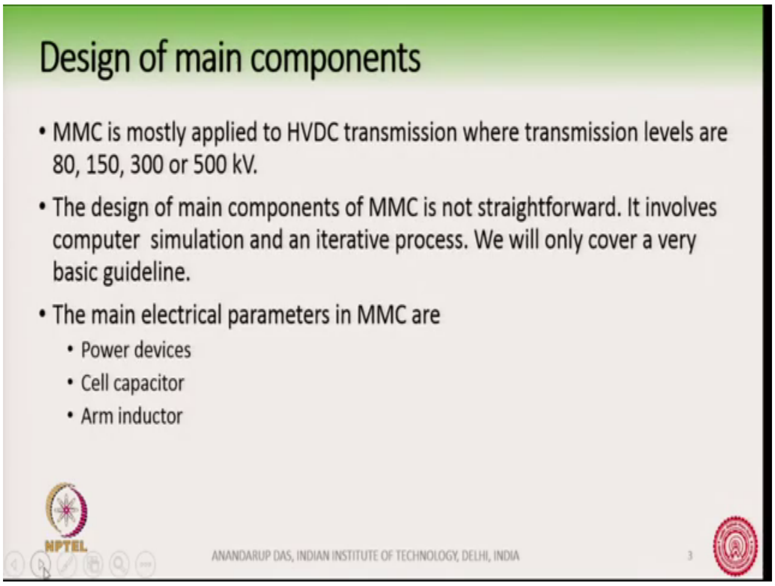

Of course, the design of this MMC component is not at all straightforward. Many computer simulations and iterations go will go on and generally a team of dedicated people work on it as covering various aspects of operation of the converter. Anyway, we will see how when we can design these power devices cell capacitors and arm inductors in this short presentation.

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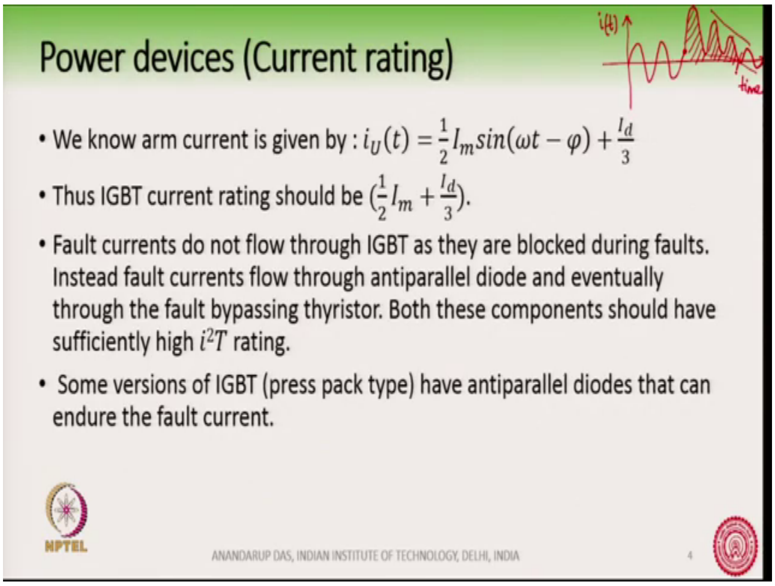

Now, if you see the current rating or the power devices you of the power devices, we see that the arm current is the arm current is given by this formula. And so, the IGBT current should be at least of this rating, at least of this much current rating should the IGBT should be and selected in the arms.

Now, fault currents; so, when a fault happens then the fault current momentarily flows through the IGBT s and within about 10 microseconds the IGBT gate drive protection will block the gate pulses and hence the IGBT will be shut off. And subsequently, the fault current will be diverted to the anti-parallel diodes. This is for a half bridge cases.

So, even with these 10 microseconds; if we see we should see that what happens during this 10 microseconds and the IGBT should be chosen in such a way that the i square T rating should be sufficiently high. So, that the fault current during this 10 micro second time should not destroy the IGBT. This should be kept in mind. Also apart from the IGBT, the fault currents will pass through the fault by passing thyristors and the anti parallel diodes.

So, these components, but this process when the IGBT has been shut off after 10 microsecond, the fault current will then be diverted to the anti parallel diode and eventually through the fault by passing thyristors; that is the fault by passing switch in parallel to the half bridge cells. So, remember that these diodes and thyristors must be having a very high i square T rating. Because the whole fault current will pass through that through those diodes and thyristors.

Generally diodes and rectifier class of sorry, diodes of rectifier class type and thyristors have generally very high i square T rating ok. So, why? This is remembered that when a fault happens, when a fault happens then the fault current. So, suppose the fault the current was initially like this and here a fault happens ok. And the fault current can go very high, the first peak can go very high and subsequently the it will fall and will come to a steady state.

Now, remember that when a fault happens, when a fault happens, then the way we protect the converter are by two ways. The MMC are protected by two ways; first we have a circuit breaker on the AC side which will open and also we have an arm inductor which will limit the rate of lives of the fault current. Now typically if this is the fault current profile, remember the circuit breaker will only operate when there is a 0 crossing of the current before that the circuit breaker will not operate.

So, therefore, when the MMC is under fault then, it is basically an RLC circuit ok. The inductor arm inductor, the cell capacitors together with the faults. So, it is an RLC circuit and we will follow it will follow a typical behavior of an RLC circuit switched at a particular instant of the AC voltage and typically the waveform looks like this. Now the waveform will decay here as per the RLC the damping time constant.

But, the ac circuit breaker will only operate after there is a 0 crossing. Now before the 0 crossing, there can be several cycles of the current. So, this is these are this is the current which is flowing before the 0 crossing here ok. And the entire i square T during this time is means that the is flowing through these diodes and thyristors and they must be rated for able to sustain the i square T during this time ok

Usually diodes of rectifier class and thyristors; they are normally designed to handle this ok. And so, there may be several cycles before the first 0 crossing happens and. So, the diode and thyristors must be able to, if the diodes are not so high then the anyway the thyristors will fire and the fault current will pass through the thyristors. Now some versions of IGBT s of anti parallel diodes that can endure this amount of fault current for such a duration of time.

So, then the then the requirement of the thyristor is reduced ok. Because, inverter class diodes do not have such very high rating i square T ok. Rectifier class diodes have very high i square T rating. So, this is something which we have to keep in mind that the fault current before the circuit breaker opens can sustain for several cycles and.

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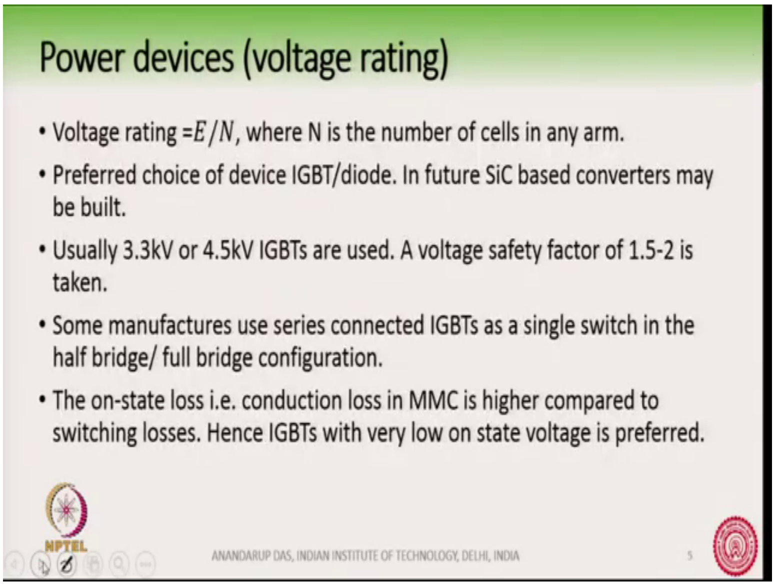

Yeah Now what should be the voltage rating? Now voltage rating is given by the available so what is the voltage across the device that is equal to E by N. Where N is the number of cells in any arm and E is the dc link voltage. Now, the as of now the preferred choice of device is IGBT or diode, but in future we see that silicon carbide based MMC s can also be built ok. Because they have higher voltage blocking capacity.

So, usually 3.3 kV or 4.5 kg i kV IGBT s are used and it is a good idea like it is a good design to keep us voltage safety factor of something like 1.5 to 2 ok. Now some manufacturers use a single IGBT in a half bridge cell and some manufacturers use series connected IGBT s as a single switch in the half bridge cell. So, you can have several IGBT s connected in series to form one single switch.

So, for example, you can have 6 IGBT s and all these 6 IGBT s is like acting as a 1 switch series connected IGBT. So, that is also a possibility. There is also one important thing is if you see the losses in MMC, the majority of the loss takes place as a conduction loss ok. Because MMC; you can see the waveform and because there are so many, because there are such a large number of cells. So, the voltage waveform is already very close to sin wave. And so, the cells need not switch very high. It can be switched very low like close to 100 Hertz something like that the each switch and the switching frequency of the switches in the cell.

So,, but the disadvantage is the conduction loss in MMC is higher compared to the switching loss. Now, therefore, we should look into IGBT s with very low on state voltage; that means, Vc on should be very low. That is those kind of devices those are very suitable for designing of MMC where the on state voltage is very loss and hence the on state loss that is the conduction loss will be substantially low. This is also something to keep in mind.

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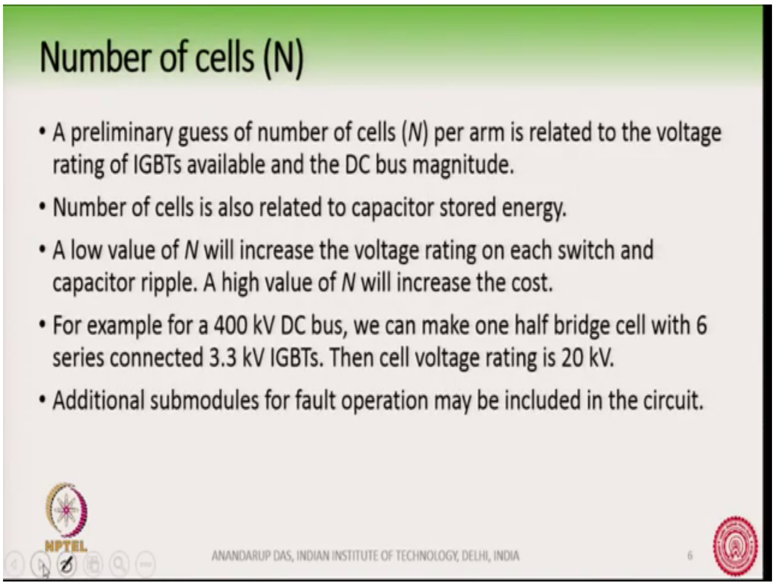

Now, how many number of cells should be used? Now a preliminary guess of the number of cells per arm is related to the available voltage rating of the switches and the DC bus magnitude ok. So, low value of N, if will increase the voltage rating of each device because the voltage rating of each device is E by N. So, if you reduce the value of N then it will increase the voltage rating on both each switch.

On the other hand if you increase the value of N. So, a high value of N, then you have many many more switches to control ok. So, it will increase the cost and complexity. So, for example, for a 400 kV DC bus, we can make one half bridge cell or the other possibilities also to use many series connected IGBT s as a single switch in the half bridge. So, you can make one half bridge with 6 series connected 3.3 kV IGBT s, then the cell voltage ratings become 20 kV.

So, you will need 20 such cells, at least minimum 20 such cells for supporting the 400kV dc bus. Of course, each cell will have a switch which is consisting of 6 IGBT s in series in the upper arm and in the upper part and the lower part also 6. So, additional sub modules for fault operation may also be included in the circuit. So, we will take a case study later and then we will see how these values can we can how do we design these values.

So, fault operation because MMC has inherent to this fault blocking capacity a fault bypassing capacity and so, we may keep 3 to 4 percent of the cells in each arm as the backup cells ok, which may be used for fault tolerant operation. How do we choose the capacitor value ok? This is something which is not very straightforward.

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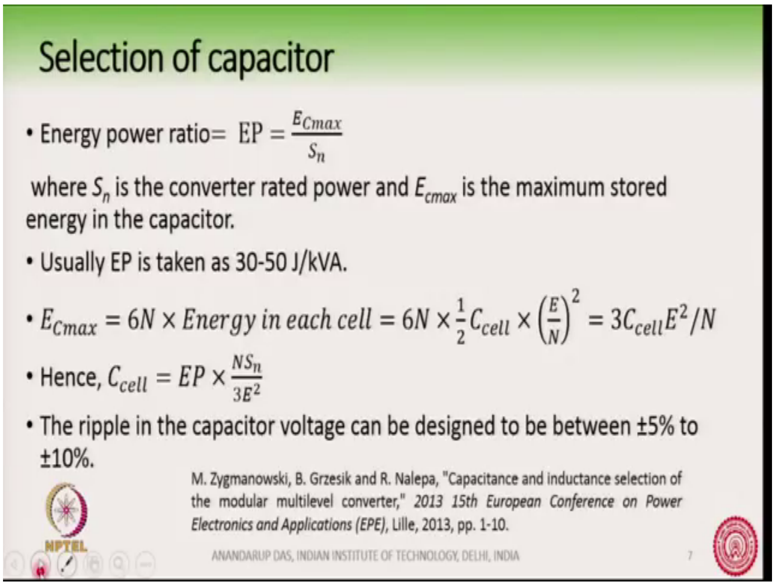

And you can see this paper for example, which gives you a little bit guidance on how to select the capacitance and inductance in MMC. But so, again this is not very straightforward and what we in order to in order to design the capacitor, what we see first is define something like as an energy power ratio. EP, which is the ratio of the maximum stored energy in the capacitor to the converter rated power. E C max divided by S n. And from the available literatures and from experience, people have taken EP to be a value between 50 30 to 50 joule per kVA.

So, if that value is chosen here, then we will be able to design the capacitance. So, if you just substitute here EC max is 6 N into energy in each cell. Now 6 N means; suppose, there are because in an MMC there are 6 arms and each arm is having N number of cells. So, the total EC max is 6 n into the energy in each cell ok. And what is the energy in each cell? That is equal to half CV square.

So, 6 N into half C cell into E by N square. Assuming that the energy the voltage on each cell is roughly E by N there is an oscillation on the cell, but we will mean energies E by N. So, therefore, 6 N into half C cell into E by N square. So, that is how we get this expression here. Therefore, the C cell is E P into N Sn divided by 3 E square. So, now, you choose the value of E P between a value between 30 to 50 joule per kVA and hence you will know what is the value of C cell.

And, you have to choose this value of C cell and can check with simulations like what is the ripple coming out to be. And, the ripple in the capacitor voltage can be designed to be like plus minus 5 to plus minus 10 percent ok. So, this is a very rough design guideline that we follow. Now yeah so, the correct value of capacitance is chosen with several iterations and in particular seen the response during fault condition.

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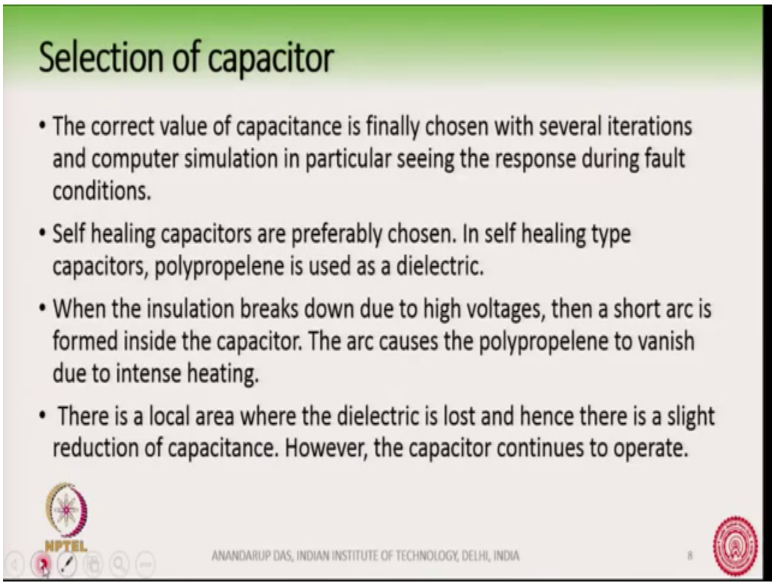

How the capacitors discharge their energy ok. Now generally the cell filling type of capacitors are chosen ok. Because it is difficult so, what is the property of the cell filling capacitors? In cell filling capacitors polypropylene is used as a dielectric. So, when there is a flashover or when there is a high voltage on that capacitor, then the insulation breaks down. And the polypropylene is polypropylene due to the enormous heat generated, the polypropylene vanish vanishes. And therefore, what happens a small arc is generated and the polypropylene vanishes and therefore, there is a local area where the dielectric is lost ok.

So, there is a slight reduction of the capacitance. However, with the loss of this dielectric, the arc is extinguished and so, the capacitor will continue to operate ok. So, this is the advantageous feature of a cell filling capacitor. So, many times, cell filling capacitors are used in this application. There is also the selection of inductor. Now the arm inductor and the cell capacitor forms a resonant circuit.

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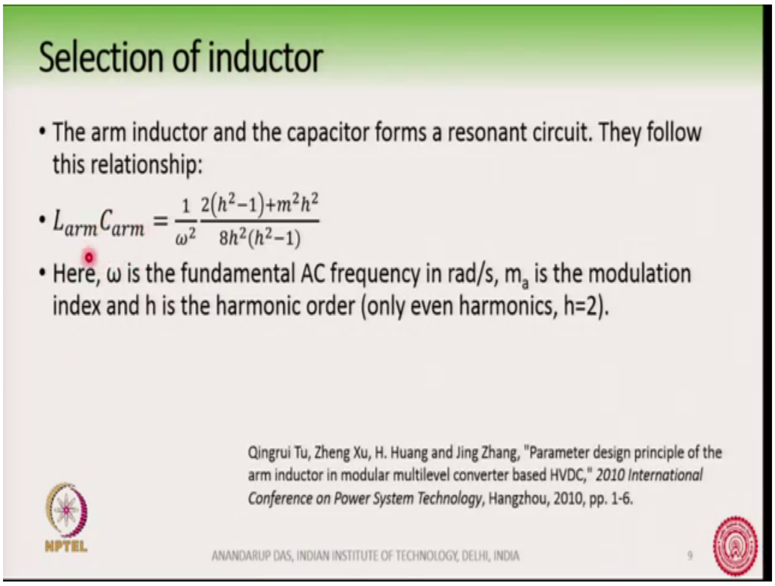

Now, again I will not go into the details of this derivation. There is a relation between them and I will direct you to this this particular article from where we get such a expression. Now you can derive this one you can it is possible to derive it, but it will be like a derivation exercise which I want to avoid right now. And so, this L arm into C arm follows this relationship. So, where the omega is the fundamental AC frequency in radian per second here and m a is the m is the modulation index and h is the harmonic order.

So, we usually take h equal to 2, because that is the most dominant harmonic present ok. So, with this expression and with the value of C arm known we can design what is the L arm or the arm inductance right.

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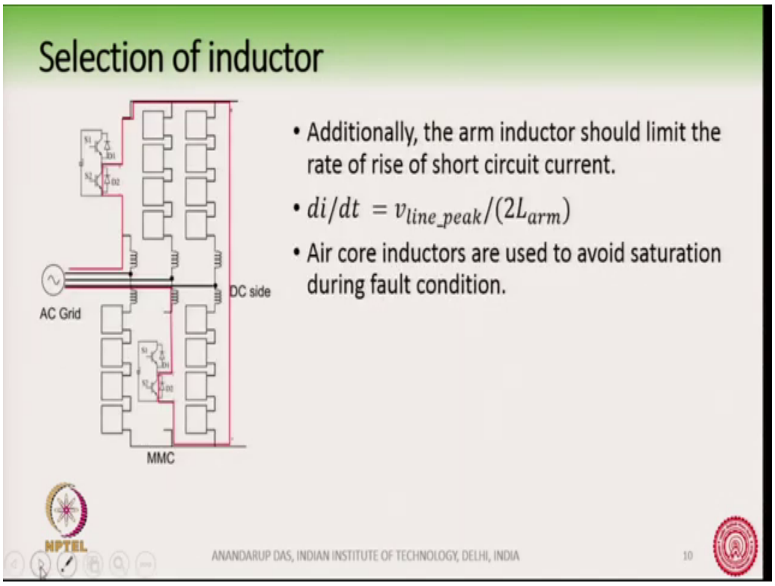

Again additionally, we should also remember that once we have selected this value of L arm, we should see that how it is limiting the rate of rise of the short circuit current ok. Remember that the short circuit current, the rate of rise of that short circuit current is happens when suppose there is a short circuit like this and on the DC side and the current is flowing like this.

Therefore, d i d t is v line peak divided by 2 times L arm. The peak for line voltage divided by 2 times L arm because there are 2 arm inductors in series. So, that is limiting the short circuit current. So, this is the rate of rise of the arm current and this value should be reasonably low. So, that the diodes and the current flowing through the diodes, they are not overly stressed.

So, this is an important criteria for designing the arm inductors. Again, usually air core inductors are used to avoid the saturation during fault condition ok. So, arm inductors are designed to keeping two things in mind. This equation here and this one here, the v line peak divided by 2 L. So, with this basic idea we will be able to design a MMC and we will take a case study and we will design the components.