High Power Multilevel Converters – Analysis, Design and Operational Issues
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Lecture – 23
Modular Multilevel Converter – PWM Technique Capacitor Voltage Balancing

So, good morning and welcome to another lecture session on the Modular Multilevel Converter. So, today we will be covering the PWM techniques and the sorting algorithm in MMC, ok.

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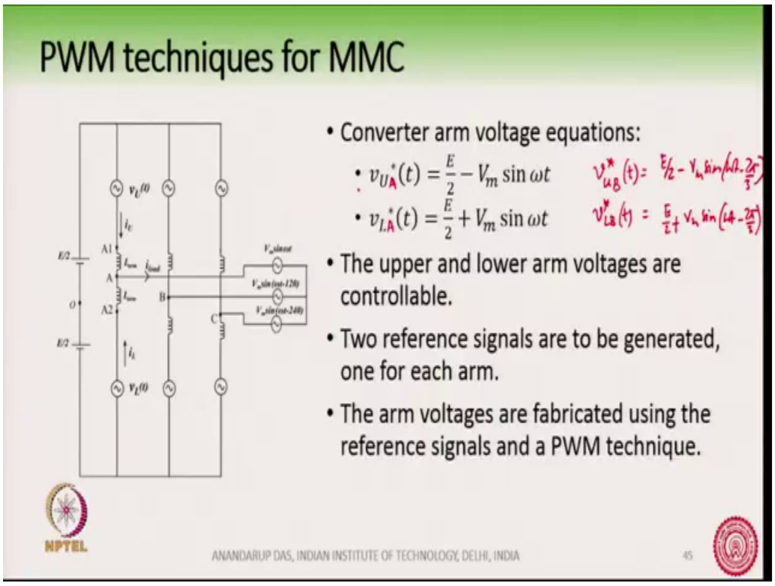

So, we will go to directly to the PWM techniques, yeah. So, the pulse width modulation technique for MMC is used to control or switch the cells or the switches inside the cells of the MMC.

So, basically we get some reference signals from the controller like conventional v s i, we get some reference signals which normally we term it as V a reference, V b reference, V c reference for a 3-phase voltage source convertor. And based on that we do a pulse width modulation, pulse width modulation is a switching action by which we control the switching sequence of the switches or the transistors inside the converter.

So, in a similar way we get reference signals for the MMC and based on this reference signals and PWM technique we will be switching the cells or the switches inside the cells.

Now, this action is very similar to what we have already discussed in during the cascaded edge bridge operation, ok. So, the we also use this level shift PWM and phase shift PWM techniques, just like what we had done in cascaded edge bridge. The same technique we will be using in case of MMC. But in addition to this PWM technique the MMC has capacitors in the DC bus, and so we will need some additional logic to balance the capacitor voltages. And this is done through the sorting algorithm which we will discuss today, ok.

But let me in order to maintain that this lecture is also kind of like somewhat independent of the cascaded edge bridge lectures. I will briefly recap, the level shift PWM and phase shift PWM techniques, and you are requested to also see those lectures wind with what we had covered in during cascaded edge bridge.

Now, from the basic operation of MMC we have understood that the arm voltages are controllable voltage sources and these controllable voltage sources are these controllable voltage sources are represented by this equations. So, v U star and v L star are the reference for the convertor arm voltages. So, which means we would like to have the we would like to have the arm voltages behaving like as per this equation, ok. Of course, this is for the AC to DC or DC to AC applications.

This reference voltages what I have written here is for AC to DC or DC to AC that is the conventional MMC applications. The reference voltages will change when we say convert from 3-phase AC to 3-phase AC or 3-phase AC to single phase AC, in those cases these reference voltages will change; however, the PWM technique is very similar for those cases also.

Let us understand the AC to DC or the DC to AC application from which we can be able to say how this can be extended to other applications. So, for the AC to DC or DC to AC application, these are the v U star and v L star, the star indicates that these are the reference voltages. How do we get it? We get it from the main control system; because the main control system for example, if it is a AC to DC rectifier it will based on how much p and q, ok, it is in case of HVDC application we generally inject the p into the DC, HVDC system.

So, we will have a reference p and from that reference p, we will be able to generate the V a star, V b star and V c star for the converter. And this v U star and v L star from is the reference voltage for any particular phase. So, this is, I should ideally write this is v U A star and v L A star. This is the A-phase reference. So, once we get the reference we will once we get the main reference from the control system, we then split it into two for the two arms this v U A star and v L A star. So, these are basically the reference voltages for the two arms in a particular phase.

For the B-phase, v U star and v L star will be E by 2 minus V m sin omega t minus 2 pi by 3. So, for the B-phase I can write, for the B-phase this is v U A star for the a phase, ok. So, similarly the v U B star that is the reference for the B-phase will be exactly similar, but, something like this. And similarly v U, v L B star is also like this, ok. And similarly you can also write the C-phase references.

So, this reference voltage is what is given to the PWM block, ok. So, the PWM block, what is the purpose of the PWM block or what is the purpose of the PWM is that you it fabricates the arm voltages based on this reference signal and the PWM technique that we are going to use, ok. And with this what we achieve is that the upper and lower arm voltages become fully controllable, ok. So, this is the basic idea of using these reference signals and the PWM technique.

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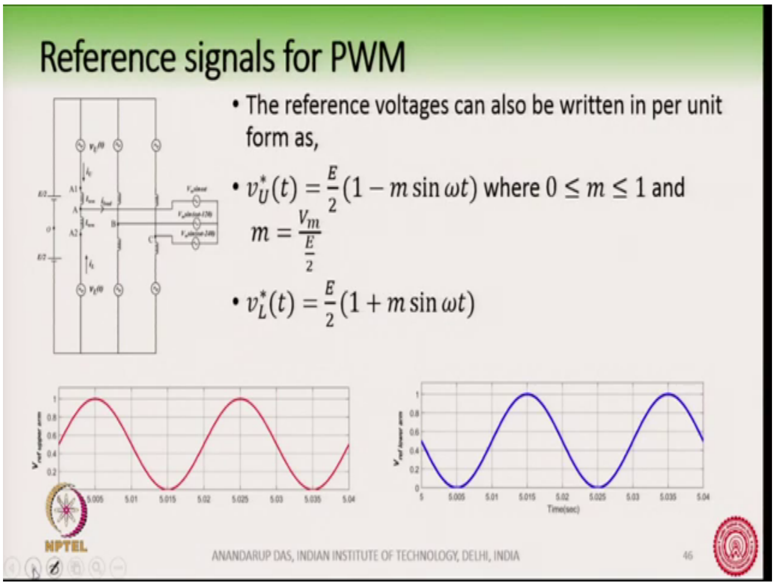

So, the reference voltages can also be written in a normalized form, ok, so or in a per unit form, right. So, you can see here this v U star, I have written it in a normalized form. So, by taking E by 2 as a common factor. So, I can write it like this where m is defined as the modulation index, ok. So, m is defined here as the modulation index and it can vary between 0 and 1 and is m is defined as the peak of the V m divided by E by 2, ok.

So, the waveforms for v U star and v L star are like this, which we had also seen earlier that this has a DC shift as well as an ac component as per the equation. Note that this reference is between 0 and 1. So, we have normalized it, now and so it is the red one and the blue one are for the upper and the lower arm. So, the we will use one PWM technique to compare this reference signal with the carriers and then accordingly switch the switches in the cell.

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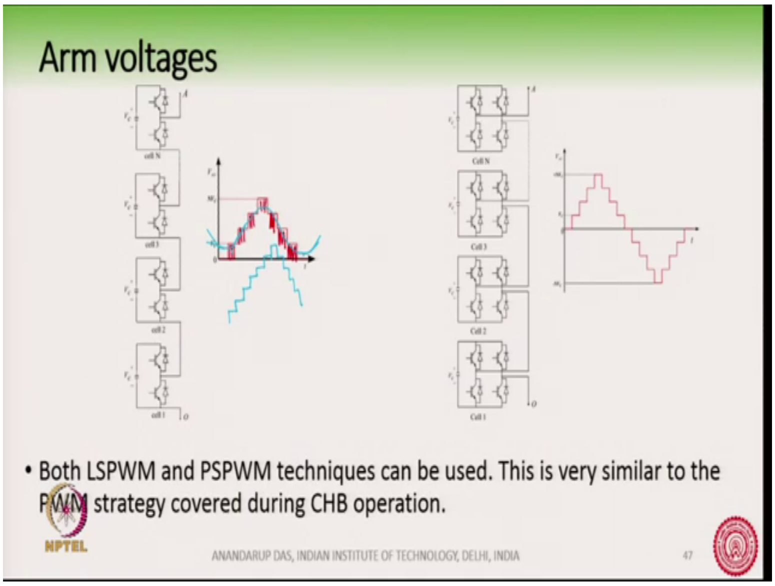

So, before I go there, just let me recap that the arm voltages from the half bridge is unidirectional in nature while the arm voltage from a full bridge is bidirectional in nature, ok. So, this is what is going to be produced from the arms, ok. So, this is what is desirable, arm voltage.

Of course, we will have a PWM here and this PWM typically looks like this, here. So, there will be switching actions here, ok. This is how the. So, that the reference voltage for example is, this is the if this is the reference. So, this is the reference voltage, ok, ok. The reference voltage lies here, ok. So, this is the actual arm voltage. Actual arm voltage is having the PWM pulses on the waveform itself.

Now, when there are many cells connected in series then, we may not use a PWM just to clarify it here. If the number of cells in the arms are very large say 100s then we may not actually even do these pulse patterns here and we can simply go ahead and just have a square wave kind of operation here, ok, if the number of pulses are very very large; because the height of the pulse becomes so small then that the PWM or the switching action is not at all needed, ok. So, if the steps are so small in size.

So, we can in order to realize this switching action both level shift PWM and phase shift PWM techniques can be used, just like what we have done during the cascaded edge bridge operation and that discussion.

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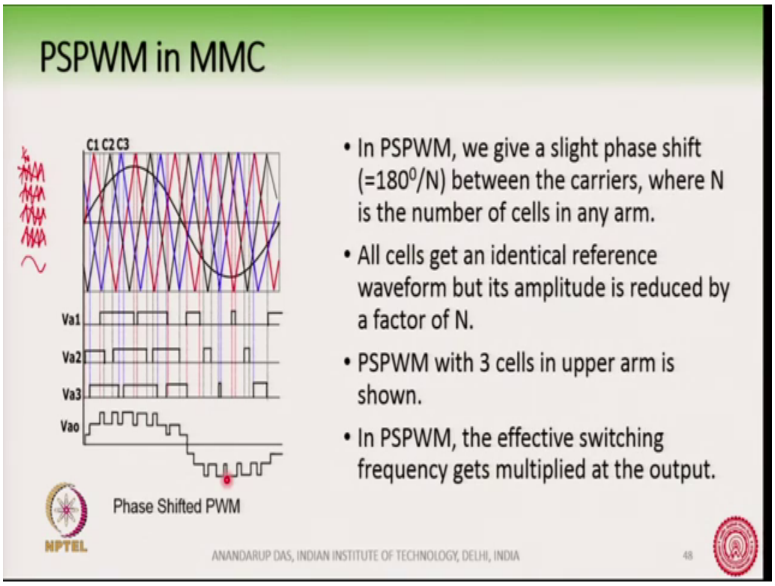

So, suppose we want to use the phase shift PWM in MMC. So, this is the, so we can see here the reference signal, this is the reference signal which we had shown, suppose this is for the upper arm and we have several carriers here, ok. We have several carriers and we know that in phase shift PWM we give a slight phase shift between the carriers, ok. So, in this case in this waveform we are having or in this converter we are having 3 cells in the upper arm, so we use 3 carrier, ok.

Now, in case of phase shift PWM, all the cells we will get an identical reference waveform, but the amplitude gets reduced by a factor of N. So, which we had said earlier also I had talked about it, that the basic idea of phase shift PWM is that each cell gets his own identical reference waveform, suppose there are 4 or 5 cells like this. So, all of them will get their identical reference waveforms and each having an amplitude of 1 by N, ok. And this we will compare with triangles individual triangles like this, but the triangles are phase shifted by a slight angle, that is why it is called phase shift PWM. And what is that angle? That angle is this 180 degree by N, ok.

And this slight phase shift between the carriers help us to push the harmonics into the higher switching frequency domain, ok. So, if the carrier frequency is f c, then if there are N number of carriers with this phase shift PWM the main harmonics shift to N times f c, ok. So, that is what I have written the effective switching frequency gets multiplied at the output, ok.

So, if you do this phase shift PWM, so MMC has a large number of cells and you can also do the phase shift PWM with MMC. So, if you have, so if this reference signal this one, this one here will be given to each cell, ok.

And, but the carriers in the cells say suppose there are 3 cells C 1, C 2 and C 3, the cells will have their own individual carriers phase shifted, and we will do the comparison like when the triangular wave is more than the, sorry when the reference wave is more than the triangle we switch on the upper device and when the when the reference wave is less than the triangle we switch on the lower device.

So, we suppose if it is a half bridge configuration we get 0 or V DC here on the output of one cell, 0 or V DC, something similarly 0 or V DC here, and 0 or V DC here. So, it will always switch between 0 and V DC because it is a half bridge cell. And then we add all of them together and we get the overall arm voltage, ok. This is the overall arm voltage that we get from the converter.

So, once we get the reference signal for the arms, it is now exactly similar to how we have already done with cascaded edge bridge by using phase shift PWM we give slightly phase shift to these carriers and we do the switching action, and the logic is pretty much repetitive what we have seen earlier.

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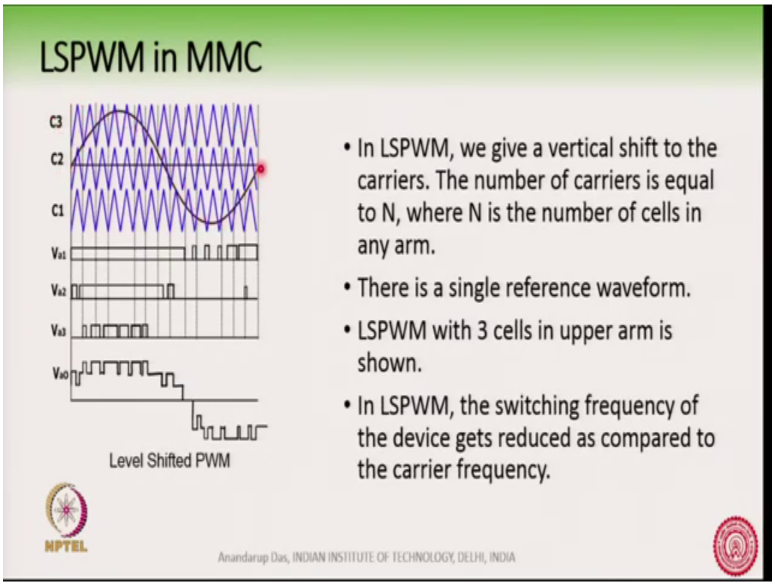

Now, what happens in level shift PWM exactly? Same, but here what we give is a vertical shift to the carriers, ok. So, the for the level shift PWM, so there is one reference waveform which we will use for switching all the cells, ok. So, the cells will have individual carriers and these carriers are vertically shifted, ok. This is say for example, for cell 1 this is the carrier, for cell 2 this is the carrier, and for cell 3 this is the carrier. But there is only one reference waveform, ok.

So, then again we follow the same logic that if the reference waveform is more than the carrier we turn on the switch otherwise we turn off the switch and suppose. So, for carrier with this carrier 1, suppose we turn on this cell we switch this V a 1 that is the output of cell 1 is controlled through this carrier and the reference. So, here the cell is completely turned on because the reference waveform is more than the carrier and here it does the switching action, here, right.

In a similar way you can see for cell 2, the reference waveform passes through the carriers here and here. So, in this section the reference waveform is more than the carrier, so it has been fully getting us clamped to the VDC voltage, here there is a switching action happening because it is passing through the carrier and here it is fully turned off. You can see it is fully turned off.

And third section is here, for the third cell like this here there will be switching action here and otherwise it will be completely turned off. As you can see here this for the third cell there are switching actions because there is something the reference waveform is crossing the carrier here, so there is a switching action here otherwise it is fully turned off, ok. So, basically the same thing and then we add these 3 waveforms to get the arm voltage, ok, yeah.

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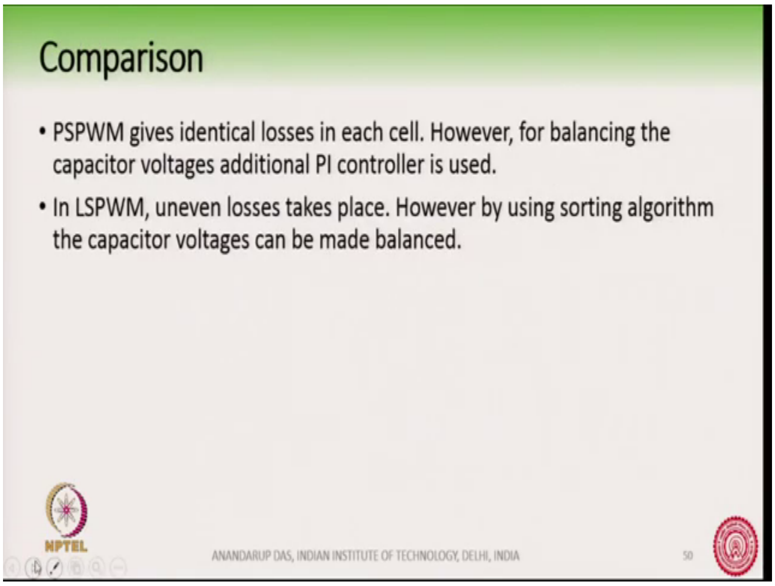

So, the phase shift PWM and the level shift PWM are basically the same strategy. We can use any one of them, but, but in case of MMC there is something else also which is to be noted, ok.

Now, phase shift PWM if you make a comparison of this phase shift PWM or level shift PWM, phase shift PWM gives identical losses in each cell because the reference waveform is same for all the cells, ok. But for balancing the capacitor voltages because the cells have capacitors on the DC bus and we have to balance those capacitor voltages, phase shift for implementing phase shift PWM we need additional PI controllers to balance the capacitor voltages.

In case of level shift PWM, the challenge is that as you can see here in case of level shift PWM the switching pattern is not same for all the cells and this will cause the uneven losses inside the cells because the switching pattern the conduction period and the switching instants are all different. So, the uneven losses will take place, but by using the sorting algorithm we can make the capacitor voltages balanced again, ok. So, these are the two comparisons of the phase shift PWM and level shift PWM, ok.

Now, in order to understand this a little bit in more details, let us take the level shift PWM case, ok, and we will see how with the level shift PWM and with the sorting algorithm we will be able to balance the capacitor voltages. So, here we will go a little bit more details into exactly how the switching is happening inside the converter or inside the arm of the converter.

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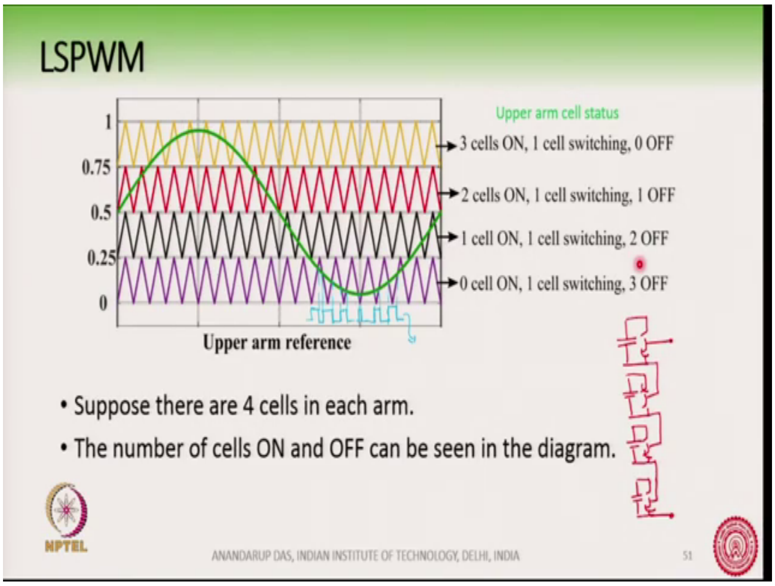

So, we have taken a level shift PWM case here. So, suppose this is the upper arm reference, and it is spanning between 0 and 1 here. So, this is the upper arm reference. And since we are using level shift PWM suppose let us assume there are 4 cells in each arm, ok. So, this is an example. So, I would like to explain this through an example, ok. We will take comprehends discrete examples and let us try to understand what is happening.

So, suppose there are 4 cells in each arm, and we want to do a level shift PWM on and try to get the desired arm voltages. Suppose this is an upper arm, so we have already got the upper arm reference waveform, that is v U star, v U. Suppose if it is an a phase v U A star we have got that reference. So, this reference is this green waveform, ok. We have got it already.

Now, we would like to switch the 4 cells in the each arm, ok. Now, you can assume that the arms are composed of half bridges, ok. We can assume that these arms are composed of half bridges. And so when you do the level shift PWM here then, so since there are 4 cells, so I have taken 4 carriers which are vertically phase shifted, ok. The modulation index is very close to 1; say about 0.9 close to 0.9, yeah here.

Now, you see here that these carriers here. So, when the waveform suppose let us take this portion of the waveform, ok. Let us first concentrate on this portion. So, on this portion, what can we observe is that, so in the power circuit, ok, we are trying to fabricate this part of the voltage, waveform.

So, from the arm, we are trying to fabricate this part of the reference waveform. So, ideally the arm voltage actual arm voltage in the power circuit should be an exact replica of the reference voltage because when we give the reference voltage we are asking the arms to produce exactly and replica of it, but amplified in the power circuit.

So, when we give this, if we consider this part of the reference waveform which is getting compared with the lowest carrier V c that out of these 4 cells, 1 cell should be doing the switching action, and the rest of the 3 cells should be fully turned off, ok. So, the 3 cells out of 4 cells, which will they will be fully turned off here because you have 4 cells and these 4 cells are needed because so there are 4 vertical parts in the waveform and these 4 vertical parts will be created or fabricated from the 4 cell output voltages.

Now, during this part of the waveform, during this part of the waveform 1 cell should be doing the switching action and how should it be doing the switching action. See, see here, so it will be doing the switching action like be turned on and there here it will be turned off and again turned on and then turned off like this. This is 1 cell. I am following the logic that if the modulating wave is more than the carrier, then the switch is turned on or the cell is turned on. So, it is like this, ok.

So, this is the waveform from the cell which is doing the switching action, ok. This on off, on off anything. The rest of the 3 cells are fully turned off, which because we do not require those cell outputs, ok. So, it is completely bypass. So, the cell structure is something like this here, sorry the cell structure is something like this. 4 cells are there, half bridges, I have assumed half bridges, right. So, this is the arm of the cell, ok. So, this is the arm of the cell. So, when I turn on this one, so it is completely bypassed or I can cell say that the cell is off whereas, if I turn on this upper switch here this one, then I cell that the cell is turned on or I get the voltage.

So, in this case I can see that during this portion of the waveform, the 3 cells have been are off and 1 cell is doing this turn on and off action or I say that it is doing the switching action. So, out of these 4 cells, 3 are completely off; that means, 3 cells are completely off and 1 cell may be doing the switching action, during this lower part of the waveform, ok.

Now, see the next carrier. See now we, so we have covered this part of the waveform. Now, let us see this part of the waveform here and here, ok these two parts of the waveform. During this part of the waveform as we know that in level shift PWM, when we are fabricating this part of the waveform, it means that 1 cell must be turned on out of the 4 cells and 1 cell should be doing the switching action.

Of course, we understand that 1 cell will be doing the switching action here because it is getting compared the reference and the carrier is getting compared here. So, there is will be a switching action here and there will also be a switching action here, ok. So, 1 cell will be responsible for doing the switching action here and here.

But there will also be 1 cell which needs to be fully turned on because it will support the waveform above this one. So, this here it will get fully turned on and it will support this part of the waveform. So, we can as if assume that this is the base region and 1 cell when it is fully turned on will give a voltage of V here, it is fully turned on. So, we go one step V and over which there is a switching action here and here which is creating or fabricating this part of the waveform, right.

And again, when we go here, again for the other perform here or here then 2 cells must be fully turned on because these 2 cells see each cell has voltage of V d by 4, ok. So, this 1 cell will be fully turned on which will support the voltage up to this point, another cell will be fully turned on which will support the voltage here and then 1 cell will be used for doing the switching action here.

So, that is why I we have written here 2 cells are fully on which means they are supporting the two voltages, 1 cell is doing the switching action here and here and 1 cell is completely off, because out of 4 cells 1 cell is not needed at this point. In a similar way, during this point and this point 1 cell has been fully turned on because it will support the voltage of this much and then 1 cell is doing the switching action and 2 cells are off, ok.

And lastly when the reference waveform is here then 3 cells must be supporting the waveform here. So, 3 cells are fully turned on, 1 cell will be doing the switching action and 0 cells or no cells will be off because all 4 cells will be needed in order to fabricate this part of the waveform, ok. So, in this way just like what we have also discussed this in a little bit in or in the when we are covering cascaded edge bridge, but I have repeated this idea here once more, in order to have kind of like more understanding about the MMC converter.

So, if we see here, this upper arm cell status we see that see if there are 4 cells we see that when the when the reference waveform is changing the instantaneous values, as the reference waveform changes its instantaneous value the number of cells which are turned on and the number of cells which are turned off is continuously varying. And 1 cell is always taking the responsibility of doing the switching action to produce the variable part of the waveform here, ok. So, this is what is, PWM.

Now, one important point to note here is that although I have said this although I have talked about this kind of a table here, I have not talked about which cell is doing what job, ok. This is to be noted. I have only talked that some cells are doing the on some cells are on some cells are off and some are doing this or 1 cell is doing the switching action. But which cell is doing what action is not told here, ok, which cell is taking the responsibility that responsibility of which cell is to be turned on and which cell is to be turned off and who will do the switching that will be decided by the sorting algorithm, ok.

But here we only understand how many cells are needed to be turned on and how many needed to be turned off and 1 cell needs the switching this much this much we understand at this point here.

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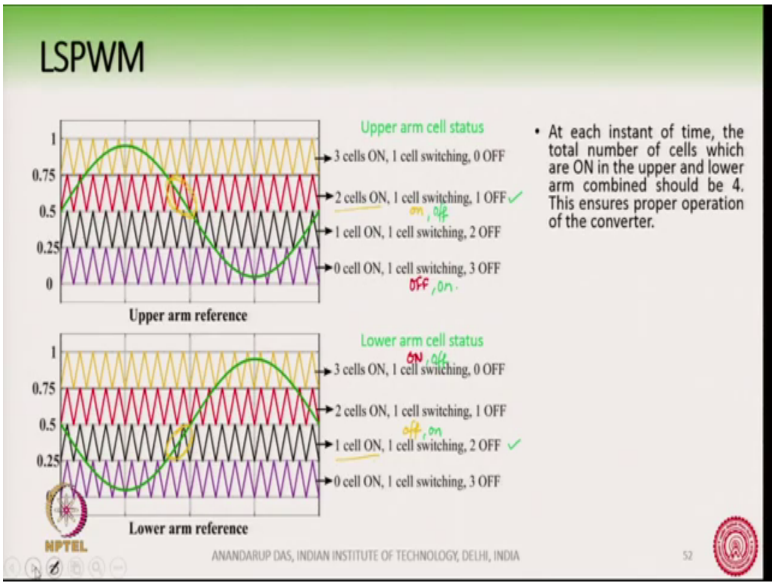

So, for the upper arm the reference waveform is like this, and similarly for the lower arm the reference waveform is like this and we follow the same logic like the upper arm, ok.

Now, here for this MMC one thing that you have to remember is that the total number of cells which are on in the upper arm and lower arm combined, should be 4, because there are 4 cells in each arm and the total number of cells which need to be turned on in the upper and lower arm combined that should be always 4 or that should be always equal to N, if there are N number of cells. This ensures the proper operation of the converter, ok

Now, why it is so, is because these if there are remember the voltage on each capacitor on the cells of the arm is equal to V DC by N. So, if there are N cells which are turned on at any instant of time then the DC bus, so the so the total arm voltage is kind of like opposing the DC bus, ok. So, if there are N cells connected or if there are N cells on in the arm then at any point of time the total arm voltage the DC component is exactly equal to the actual DC bus voltage magnitude because each arm each cell has a voltage of V DC by N.

So, therefore, we always would like to keep that keep that level equal, like the total DC bus voltage is equal to the sum of the capacitor voltages from the total arm, from the total leg, so sum of the upper arm and the lower arm. So, the total number of cells which are on in the upper and lower arm combined should be 4 because the sum of, and so the each capacitor voltage is V DC by 4, ok. And so if 4 cells are turned on, so the total voltage which is opposing the DC bus voltage in the leg that is the upper arm and lower arm combined in the leg, the total voltage is V DC and they are matching. So, that is why we always keep it equal to N.

This ensures the proper operation of the converter. You can violate this condition, but then suppose the DC bus voltage is VDC and the total leg voltage is not VDC then you will see that the circulating current magnitude drastically goes up, ok. So, we have to ensure that for the proper operation of the converter this value that the total number of cells in the upper and lower arm combined or in the leg is always equal to N or 4 in this case.

So, that you can see here, that for example, you have if you see for example, in this portion of the waveform say from this to this time instant the upper arm is here and the lower arm reference is here. So, for the upper arm 0 cells are on, 1 cell is doing the switching and 3 are off whereas, for the lower arm 3 cells are on and 1 cell is doing the switching and 0 are off.

So, you can see here that the total number of cells, you can see that is equal to 3 cells on and 1 cell this and this cell are complementary, it should be complementary in action, because then only you can make sure that there are sometimes 4 means there are 4 cells which are turning on. So, here 3 cells on and if this is on and this is off, ok, so then you have 4 cells. So, means if for the upper and lower arm if you see this if this is on and this is off, so then there are, so suppose let us, so this is on and this is off the 2 cells which are switching, the 2 cells which are switching in the upper arm and the lower arm they are complementary, ok. So, if this is on, then this is off.

So, you can see that at any instant of time the total number of cells in the upper and lower arm combined is equal to 3 plus 1, 4. When the other case happens then this becomes off and this turns on. But again you see that the sum of the cells. So, this there are 3 cells on here and 1 cell on here, the sum is again in the leg is 4.

In a similar way, you can take up any other case. Suppose you take this part of the waveform here. Say you take this part of the waveform and so this part of the waveform and this part of the waveform, here. So, here you see 1 cell on, 2 cells on, so the total sum of cells on is 3 and of course, 3 are off. And 1 cell is doing the switching, but when this turns on it will be off and when this is off then this will be on. So, you see that if you take this and this part then here also the number of cells in the total leg is again 2 plus 1 plus 1, that is 4 cells are on, 4 cells are off all the time, ok. And this must be ensured for the proper operation of the converter at any instant of time, ok. This must be kept in mind.

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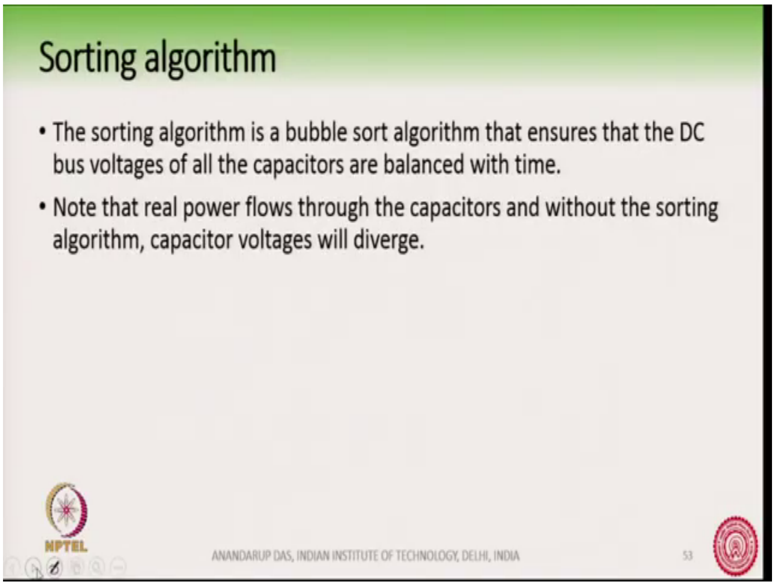

Now, next comes what is called the sorting algorithm, ok. So, why is the sorting algorithm needed? So, although, so first thing is we have understood that the arm voltages are made up of capacitors and real power is flowing through the capacitors and without some kind of a sorting algorithm the capacitor voltages will diverge. So, what happens is why the sorting algorithm is needed is that the sorting algorithm ensures that the DC bus voltage of all the capacitors are balanced with time, ok.

So, it may happen that since the capacitor voltages are in means without the sorting algorithm the capacitor voltages will start to diverge. So, we will take an example and then we will understand why this sorting algorithm is needed and how it functions, ok. The basic idea here is that the DC bus voltages of all the capacitors have to be made same over time, ok. This is what is ensured by the sorting algorithm.

So, let us again come back to the example and try to understand the sorting algorithm.

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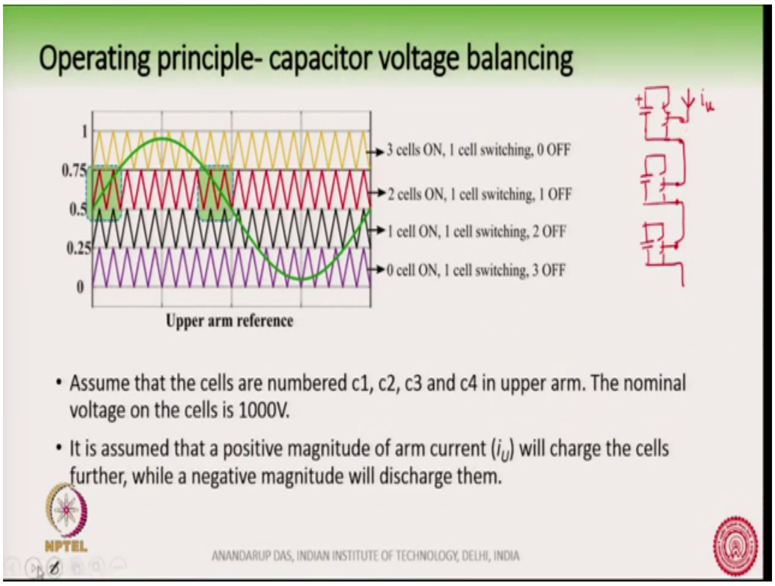

Now, we in order to understand it, let us again take this part of the waveform. We have taken two shaded portions of the waveform here and here, and again we take the assumption that there are 4 cells in each arm. And from the PWM technique which we have discussed we find that 2 cells need to be turned on, and 1 cell needs to switching; because 2 cells because you are supporting the voltage here and 1 cell needs the switching here the PWM switching will happen here and one will be off, ok. Now, the question is which cell will be on and which cell will be off? Ok. This is decided by the sorting algorithm.

So, let us again assume that the cells are numbered c 1, c 2, c 3, c 4 in the upper arm, ok. There are 4 cells which are numbered c 1, c 2, c 3, c 4 and the let us take an example the nominal voltage on the cell is 1000 volt, ok. So, we would like all the capacitor voltages to be balanced at 1000 volts that is the DC bus. There will be always an oscillation over it, but overall it will be balanced at 1000 volt. How can we do that?

Now, now again there is another assumption that a positive magnitude of current i U will charge the cells further, while a negative magnitude will discharge them, or yeah. So, like what I wanted to say here is that, suppose the cells are like this. So, this is the half bridge which we have, ok.

So, this is suppose i U, and when I say that the positive current will charge the cells up means that if you turn on this, so this current will charge up this cell here, ok. So, when the cell is turned on; that means, when the upper switch is turned on, then this current the positive direction is such that it will charge up the capacitor voltages further. And if again the current is negative it will discharge it, so we are assuming this kind of a circuit connection and this is the assumed direction of the current.

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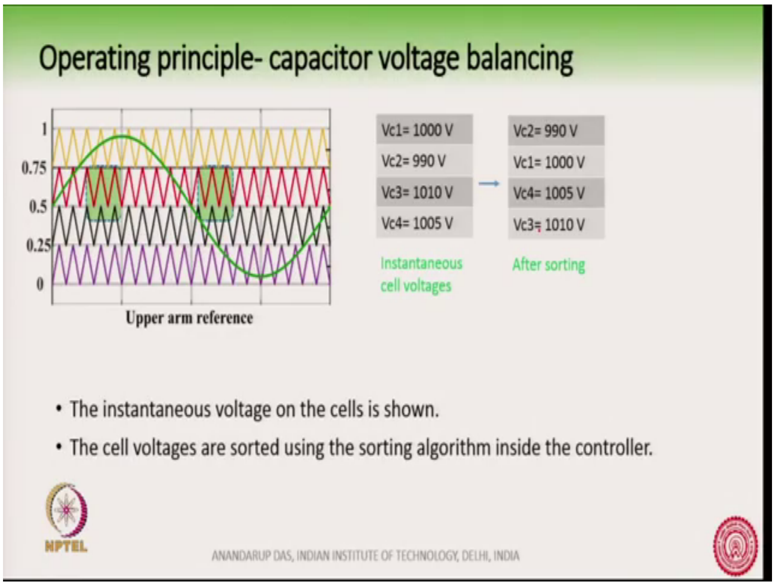

Now, suppose at any so, this has shifted, sorry for that these two zoomed areas have shifted. I would have actually. These are the two zoomed areas. So, in this figure there is a mistake that the zoomed areas have shifted, I think, yeah. So, while doing the copy paste from the previous slide to this slide I have made a mistake, but you can assume that this zoomed area should have been here and here, anyway.

So, at during this zoom area at any instant of time the V c 1, there are 4 capacitor voltages and their voltages are something like this 1000 volt, 990 volt, 1010 volt and 1005 volt, ok. This is the instantaneous cell voltages, ok.

The first step in the sorting algorithm is that we sort these 4 voltages, suppose we use a bubble sort algorithm and we sort it from low to high. You can also do from high to low, but you just sort it in ah, ok. So, you can sort it like 990. So, if you sort these voltages then, so 990 volt here, 1000 volt 1005 and 1010 volt and these are the and this sorting these are the capacitor voltages and this sorting is done inside the controller, inside the DSP for example.

So, the cell voltages, the instantaneous cell voltages are usually obtained from the ADC or the analog to digital controller. It will sense the voltage and this information will come to the controller. The controller will then do a sorting of these voltages and it will make a new such a table here. So, 990, 1000, 1005 and 1010 voltage volt.

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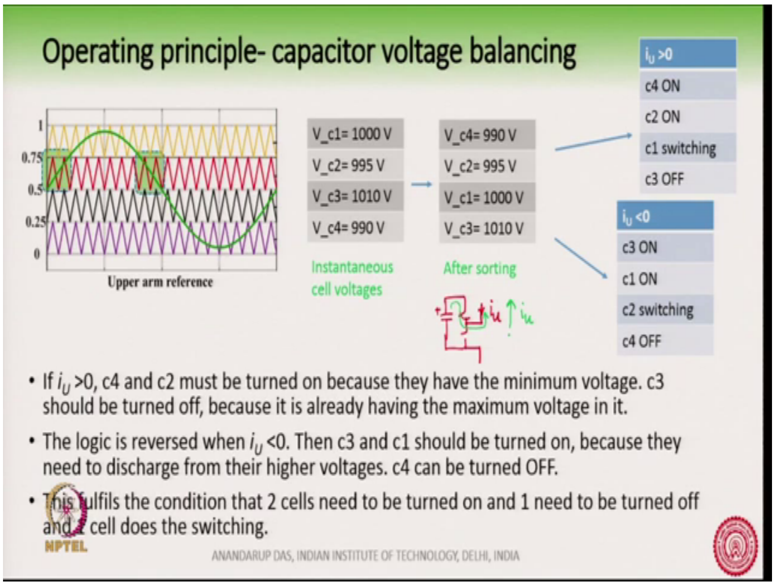

Next, what happens? You see here that now we have to decide which cell needs to be turned on, which cell needs to be turned off and which means one will be doing the switching, right because during this portion remember I told you we have, see in during this portion 2 cells need to be turned on and 1 cell will be off, 2 cells need to be turned on, 1 should be off and 1 should be doing the switching.

Now, which cell will do which job? Ok. So, after this sorting after the sorting we have found that this is the status of the capacitor voltages, ok. c 4 is minimum, c 3 is maximum and c 2 are, c 2 and c 1 are in between, the voltages on this. Now, if i U that is the upper arm is positive, ok. So, upper arm is positive means, so let me just quickly also draw it here somewhere upper arm positive means, ok, i u is positive here.

So, what we need during this portion? We need that c 4 should be turned on and c 2 should also, because we need to turn on 2 cells, we need to turn off 1 cell. Who will be turned on? c 4 and c 2 will be turned on; because they have the least voltage out of the 4, ok. If I turn on c 2 and c 4; that means, I turn on this switch, I turn on this switch then I see that c 4 and c 2 will be charged up. It will be charged up the voltage will increase because i u is in positive direction. This is the direction of i u and out of the 4 cells 2 cells need to be turned on and the cells which need to be turned on must be c 4 and c 2 because their voltages are minimum at this point of time.

Which cell needs to be turned off? 1 cell needs to be turned off and dip it must be c 3 during this point because c 3 has the highest voltage 1010. So, that is why we have written here c 3 should be turned off. And of course, the one who is left is the one which should get the switching action. So, V c 1 is 1000 volt it will get the switching action, ok.

So, we have to turn on and off the cell c 1. So, cell c 2 and c 4 will be fully turned on, cell c 3 will be fully turned off, and cell c 1 must be doing the switching action. And what is the effect of that? The effect of that is that c 4 and c 2 will climb up; the or the voltage on the c 4 and c 2 will increase, while c 3 will be totally bypassed and each voltage will stay constant and the voltage on c 1 will be slightly increasing not as not as much as c 2 and c 4, but it will also increase because we are doing the switching action, ok.

Remember that we are using half bridges. So, half bridge means if you turn on the upper switch we will charge or discharge the capacitor based on the direction of i u, but if we turn on the lower switch then we are bypassing the cell, so the capacitor voltage will stay where it was.

So, now the question is, so this is what we I have written i U greater than c 4 and c 2 must be turned on because they have the minimum voltage; and c 3 should be turned off because it has already the maximum voltage. Now, in case i U is less than 0, if i U is less than 0, what will happen? It may happen that during this instant of time i u instead of flowing like this way, i u is flowing like this way. Then what we should do? What should be your algorithm? The logic will be reversed, ok.

So, then what we will do? We again we have to turn on 2 switches and we need to turn off 2 switches, turn off 1 switch. So, which 1 should be turned on? You see, when the direction of current is like this when the direction of current i u is like this the capacitors will discharge, ok.

So, I will of course try to discharge c 3 and c 1 because they have the highest voltage, right. Since they have the highest voltage c 3 and c 1 they have the highest voltage, so I have made c 3 fully turned on and c 1 fully turned on here, because with that what is possible is that I will be able to discharge both c 1 and c 3, right because the current direction is this way. So, the current is going out like this, ok. So, it will discharge, the capacitor voltages will discharge.

So, therefore, c 3 and c 1 has to be turned on because we want to get a lower voltage from them. c 4 must be turned off because c 4 is already at the minimum voltage. And if you discharge it further is going to go down further. So, c 4 is off, and so, we are off means we have turned on the lower switch of c 4 and c 4 the capacitor voltage will stay at 990 volt, it will not divert. And again, the intermediate fellow is c 2 and it will do the switching, ok. And during this course of switching it will also slightly discharge, because the current direction is like this, ok.

So, by this algorithm we see that over a certain period of time by doing this round robin thing or like someone comes in someone goes out some cells come in some cells go out. By doing this action repeatedly over time, we can ensure that the capacitor voltages or the DC bus voltages on all the cells in the arm they are balanced over time, ok. So, the first step is the level shift PWM or any PWM technique and second step is ensuring that the sorting algorithm is implemented, ok.

You also understand that in order to implement the sorting algorithm we need to sense the capacitor voltages in each DC bus. So, there must be a voltage sensor and there must be also an arm current sensor. So, this arm current sensing is essential for knowing the status or the direction of the current whether i U is greater than 0 or whether i U is less than 0. So, this is kind of like this is inbuilt in MMC where you sense the two arm currents and all the capacitor voltages because without that you will not be able to you will not be able to balance these capacitor voltages, ok.

So, another thing which I would like to mention here, you will talk about this control system later, but this ensures that individual capacitors inside the arm they are balanced, ok. However, the total arm voltage that is the sum of the voltages it may diverge. So, we must have a control which ensures that the total arm voltage is constant over time, ok.

Now, why? For example, see these are 1000 volts, the total arm voltage is say 4000 volt. So, the sorting algorithm, what it ensures is that out of the total arm voltage of 4000 each capacitor voltage is balanced at 1000 volt. But if the total arm voltage changes from 4000 total arm voltage is increasing, say 4000 to 4200, 4300, 4500, the total arm is voltage is increasing then internally the sorting algorithm does not look for that. It just ensures that the capacitor voltages are 4500 divided by 4. So, the capacitor, the sorting algorithm ensures that the internal voltages on the cells are V DC by N, arm voltage divided by N. So, we need to have a controller which ensures that the total arm voltage is also kept constant over time apart from the sorting algorithm.