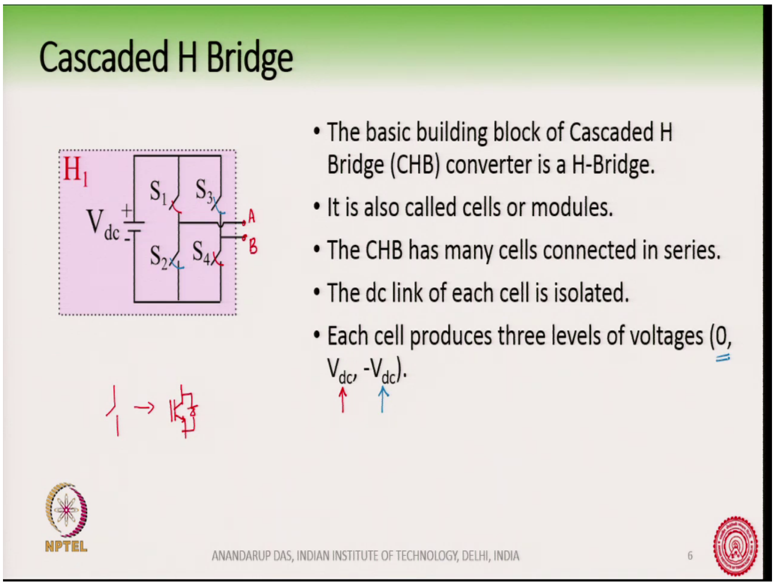
High Power Multilevel Converters - Analysis, Design and Operational Issues
Dr. Anandarup Das
Department of Electrical Engineering
Indian Institute of Technology, Delhi

Lecture - 12
Cascaded H-bridge Multilevel Converters

(Refer Slide Time: 00:17)



Now, the basic building block of this Cascaded H-bridge multilevel converter, in short CHB; CHB multilevel converter or CHB converter is H-bridge which we have shown in this diagram here and we have also studied it earlier how H-bridge works.

I have shown generic switches here S 1, S 2, S 3, S 4. Basically each of these switch is a combination of a transistor and an anti parallel diode ok. So, I mean this switch is it can be say if I do with a IGBT, it switches like this ok. We have seen that this H-bridge is the basic building block of the CHB multilevel converter. It also has a DC source which is represented by V dc. In some cases this DC source can be capacitor and in some cases, the DC source can be fed from a rectifier; in some cases, it can also be for example, can be connected to a PV energy source or PV panel.

This building block or this H-bridge is sometimes called a cell or a module and the CHB has many cells connected in series. The word itself says cascaded H-bridge. So, we are cascading several of these H-bridges together, we are series connecting them; cascading series connecting. The dc link of each cell is isolated.

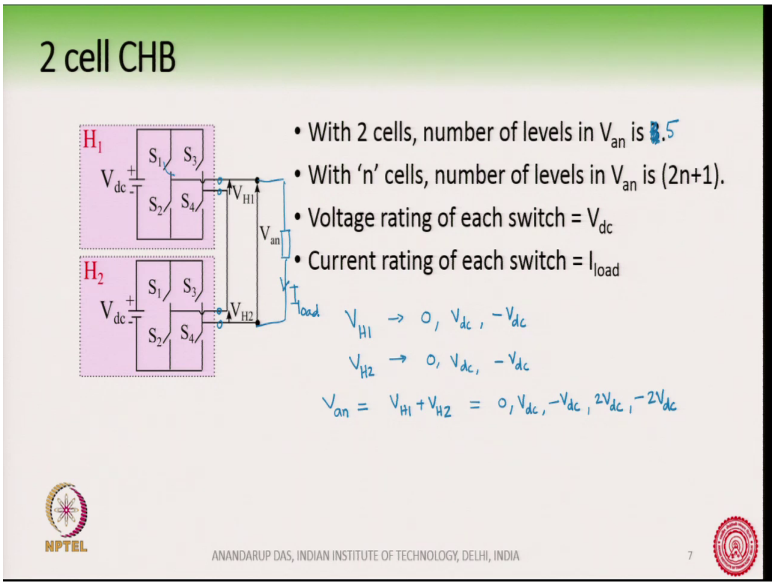
So, when we cascade them, I will show you, when we cascade them, we have isolated dc links for each of these cells or modules. Now, each cell if you see each cell produces three levels of voltages. So, this is the output of the cell ok. Here is the output of the cell and if. So, here this voltage can assume three levels; I mean three distinct magnitudes of voltages are possible at this point here.

So, suppose if we turn on S 1 and S 3 ok, if we turn on S 1 and S 3, then this voltage here is 0 right because this is connected to this and then, this is connected this. Similarly, if it can turn on S 2 and S 4, the voltage here will be 0. If we turn on S 1 and S 4, if we turn on S 1 and S 4 that is the diagonal switches or S 2 and S 3 we can get either plus V dc or minus V dc.

So, by turning on this diagonal switches, we can get plus V dc or minus V dc. So, for example, if S 1 is turned on and S 4 is turned on and this voltage; if I say V A B; so, if we turn on S 1 and S 4, then V A B voltage will be equal to plus V dc. In this case V A B voltage is plus V dc, this one ok. On the other hand, if we turn on the S 3 and S 4, if we turn on S 3 and S 4; then, the V A B voltage is minus V dc, this one ok.

And of course, when we connect when we turn on S 1 and S 3 or S 2 and S 4, we get 0 voltage here. So, there are three voltages available from one H-bridge or one cell. Of course, we cannot turn on S 1 and S 2 simultaneously or S 3 and S 4 simultaneously, then we will short the DC bus. So, S 1 is complementary to S 2 and S 3 is complementary to S 4. This we have to maintain all the time.

(Refer Slide Time: 05:07)



Now, what will happen, if we connect two such H-bridges together ok? So, we have now H 1 and we have now H 2 and we have connected two such H-bridges together. How did we connect? This was the output of one H-bridge and this one is now connected to this point and this is the output of the second H-bridge and we have connected them in series. So, V H1; V H1 and V H2 the voltage passable from V H1 and V H2 are independent of each other.

So, V H1 can have 0 V dc or minus V dc that we had seen earlier. What about V H2? V H2 is operating independent to V H 1. So, it can also generate 0 V dc and minus V dc. Now, what is the voltage V an? What is the voltage V an? V an is nothing but the sum of V H1 and V H2. So, we can make this sum. So, I take 0 here, suppose V H1 is 0. So, 0 plus 0 is 0. So, this is one possibility; 0 and V dc is V dc this is the second possibility; 0 and minus V dc is another possibility ok.

Take now V H1 as V dc. So, V dc and 0, V dc plus 0 is V dc, we have already written this. V dc plus V dc is 2V dc and V dc plus minus V dc is 0 which we have already written. What is the third option? V H1 is minus V dc. So, minus V dc plus 0 is minus V dc, this is written here; minus V dc plus V dc is 0 written here and minus V dc and minus V dc is minus 2V dc.

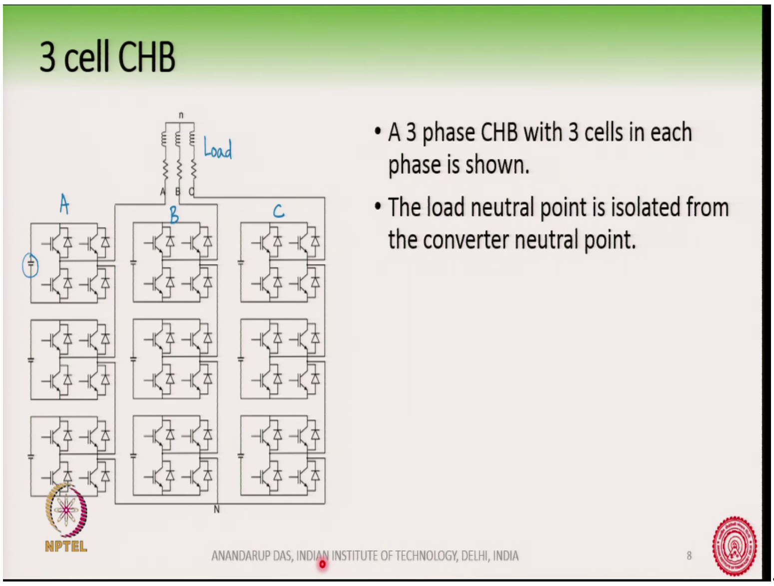
So, we see that V an can have five levels of voltage; 0, V dc, minus V dc, plus 2V dc and minus 2V dc. So, with two cells number of levels in V an is 5. So, there is a mistake here. So, this should be 5. With 2 cells number of levels in V an is 5 and these are the five possible voltage levels ok. Now, if you connect more number of cells say if you generalize it, if you connect n such cells; then number of levels in V an will be 2 n plus 1.

Now, remember that the voltage rating of each switch in each cell is V dc, why the voltage rating is V dc because if you for example, turn on this device the voltage that needs to be blocked by S 2 is V dc and hence, the voltage rating of each switch I mean these switches are all identical. The voltage rating of all of them is V dc throughout and the current rating of each switch is equal to I load, I mean if we connect a load here for example, suppose we connect a load here across V an. Then, this load current will flow either means it can flow through any of these four switches and it can also flow through any of these four switches based on the switching combination.

So, the rating of this switches will be equal to I load, where I load is this one. So, we see that all the voltage all the switches are identical in terms of their voltage and current rating. The voltage rating is V dc and the current rating is I load. So, this is one feature of such converter in that is that this converter has a high degree of repetitiveness or in one way, we can say it is highly modular because H 1 and H 2, these are two identical identically rated H-bridge cells.

So, if we produce one such H 1, we can very easily manufacture H 2 or H 3 or H 4 like that. So, it is highly repetitive and modular in structure. So, it is very advantageous to produce such cells in mass production and it is when you whenever you can produce any product in in a mass product, mass production fashion then the cost reduces substantially. Because you need to produce one such cell within a very detailed and with a considerable time and effort, but once that cell has been properly manufactured and tested, then it is a matter of repeatating repeating the process and producing many such cells. So, we see that the CHB has inherently this feature.

(Refer Slide Time: 11:41)



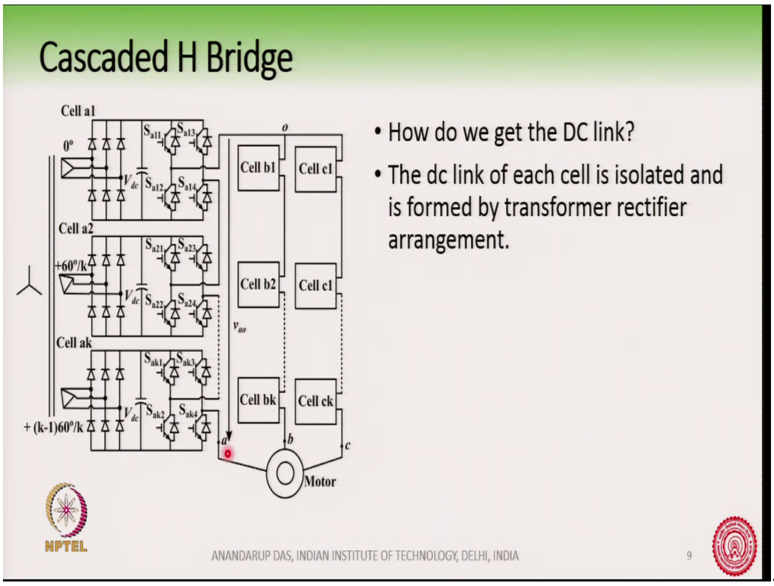
So, how do you now connect or how do you get a three-phase converter? I have shown this with 3 cell CHB here. So, this is for example, phase A; this is phase A; this is phase B and this is phase C. This is the load here; here is the load and here is the converter; here ok.

So, in phase A, we have 3 cells; cell 1, cell 2, cell 3; here. These three cells are cascaded. So, you can see that the output of cell 1 goes to the input of cell 2; output of cell 2 goes to the input of cell 3 and so on. So, there are three such cells in each phase and altogether in three phases, we have 9 cells. Note that all these cells all these cells have isolated DC sources. So, all of them are fed from isolated DC sources, we will see how these isolated DC sources are made.

You can have more than three cells. You can have 4 cells, 5 cells, 6 cells like that and you can then, have a generalized n cell cascaded H-bridge. One point to note is this neutral point here ok, the end point of this A phase, B phase and C phase are connected together at this end point here, neutral point. This neutral point here is isolated from the neutral point of the load. Usually, they are all isolated and there may exist a potential difference between this point here and this point here; the load neutral point and the converter neutral point.

We can also we will see sometimes later that because this capital N and small n are isolated from each other, we will during fault operation it is possible to bypass some of the cells and we can have a common mode voltage which takes the benefit of isolation between capital N and small n we will see that later.

(Refer Slide Time: 14:53)



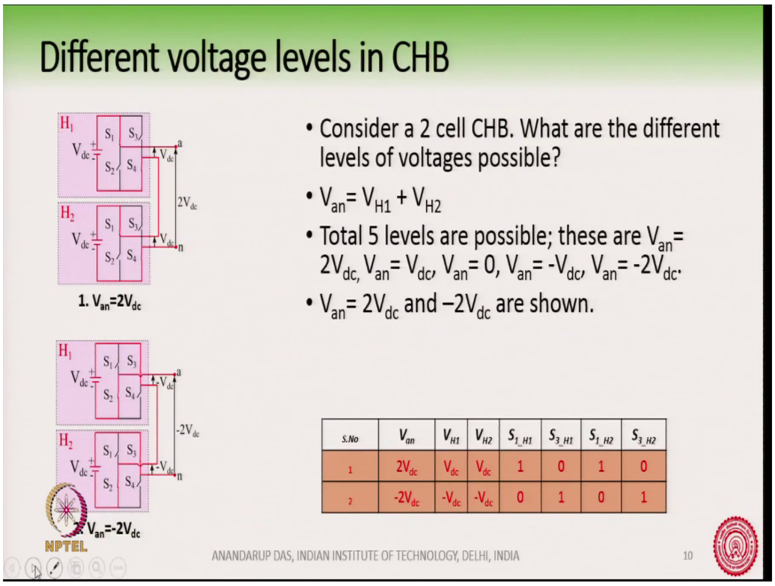
How do we the real converter looks like say for example, we are supplying to a motor load here and this is say B phase, this is C phase and this is A phase which is shown with the detailed circuit and if you see one cell in phase A, these are the 4 transistors or IJBTS with anti-parallel diodes. But the DC link, the DC link here earlier we had shown with a battery symbol, but often this DC link is made with rectifiers.

So, three phase rectifiers with a capacitor here that forms the DC link and this DC link is isolated from the DC link of the next cell and from the next cell. We often have transformer which has a primary and several secondaries like this and these several secondaries or each secondary is connected to the respective rectifier.

So, we have similar arrangement for cell in B phase and for cells in C phase. So, basically it is quite a big converter with input rectifiers, capacitors and then, cells and then these cells are connected in cascade. But this transformer with one primary and several secondaries actually helps in improving the power factor of the current which is drawn at the transformer primary.

So, basically it is a multi pulse rectifier and the THD or Total Harmonic Distortion of the current drawn from the input is very small. We will talk about sometime later not while discussing about CHB because in CHB, we will be focusing more on this side here; where, we will assume that there is a steep DC source with the battery and then that these cells are connected in series.

(Refer Slide Time: 17:37)

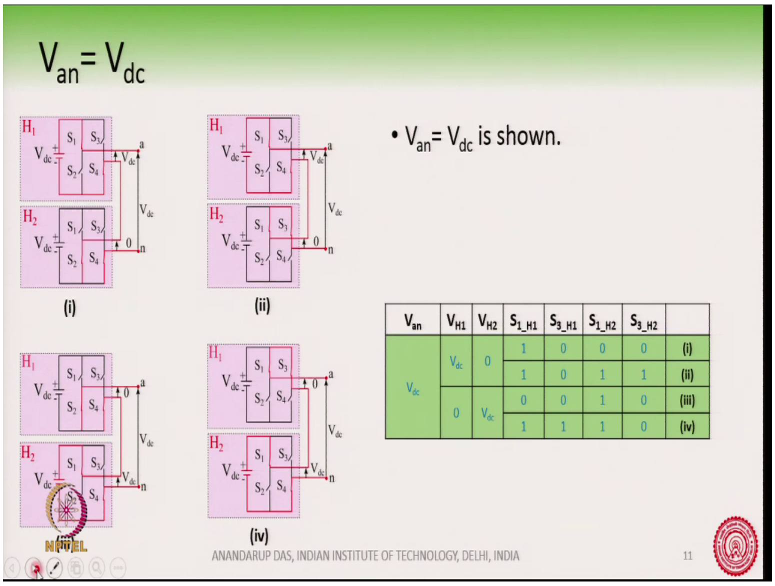


S.No	V_{an}	V_{H1}	V_{H2}	S_{1_H1}	S_{3_H1}	S_{1_H2}	S_{3_H2}
1	$2V_{dc}$	V_{dc}	V_{dc}	1	0	1	0
2	$-2V_{dc}$	$-V_{dc}$	$-V_{dc}$	0	1	0	1

So, here we are showing detailed circuit for getting the five levels of CHB. Suppose, we have a 2 cell CHB and so, the V an voltage here is as I had earlier told you is equal to V H1 plus V H2 and so, if we so this is also shown in this table here, the same thing with the detailed switches, the status of all the switches also shown. So, if V an is 2 V dc of course, V H1 will be V dc and V H2 will be V dc and so, in order to get V H1 as V dc we should turn on S 1 and S 4 as shown here.

And similarly, if we want to get minus 2 V dc in V an, then we need to have V H1 as minus V dc and V H2 as minus V dc because their sum will be equal to minus 2 V dc. In order to get minus V dc we should have S 3 and S 2 turned on, as it is shown in this diagram and from this second cell S 3 and S 2 turned on, this diagonal switches in these two cells will give us this minus V dc. So, minus V dc and minus V dc and like this.

(Refer Slide Time: 19:25)



In a similar way as we as we have written here, so this was for V an equal to 2 V dc or minus 2 V dc; that means, we this circuit are showing the status for this one and for this one. Now, if we want to get this V an equal to V dc; how is the circuit? It is shown here. Now, for V an equal to V dc; that means, I want to get V dc voltage here. Then, there are several possibilities. In fact, there are four possibilities; what are these four possibilities?

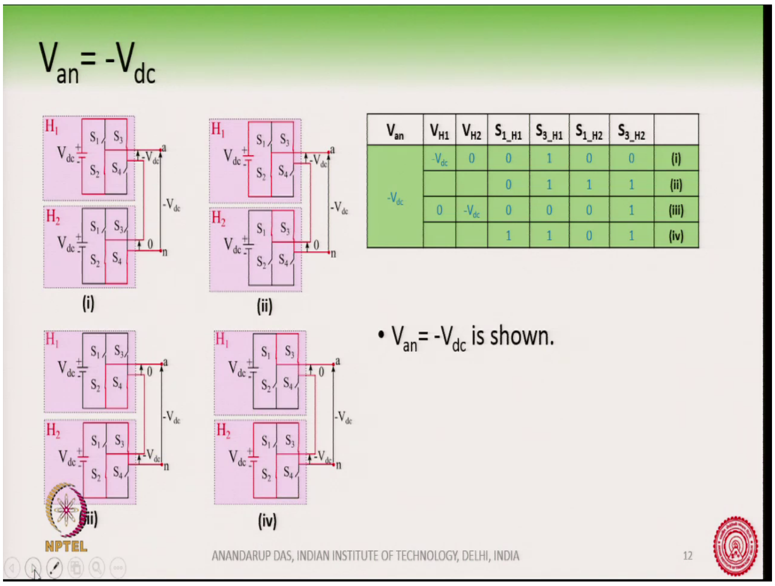
The possibilities are V H1 is V dc and V H2 is 0, this is one possibility. The second possibility is V H1 is 0 and V H2 is V dc ok. So, this is what is shown here. So, V dc when we want to get V an as V dc, it can be V H1 V dc V H to 0 or V H1 0 and V H2 V dc because V an is nothing but V H1 plus V H 2.

Now, for getting V H1 as V dc and we have one switching combination that is S 1 in H 1 is one and 0, H3 is 1. So, this is the these are the two switches, if you want to get V dc out of V H1, then we have to turn on this S 1 and S 4. But when we want to get 0 from V H2 then we have to switching state possibilities or to switching combination are possible; either we turn on S 2 and S 4 or we turn on S 1 and S 3, both of them will give me 0 out of V H2.

So, there are two switching state or switching combinations possible in order to get 0 voltage or we can say that in order to get this combination V dc and 0, there are two switching multiplicities possible; the word multiplicity is used here that there are two switching multiplicity is possible in order to get this V dc and 0.

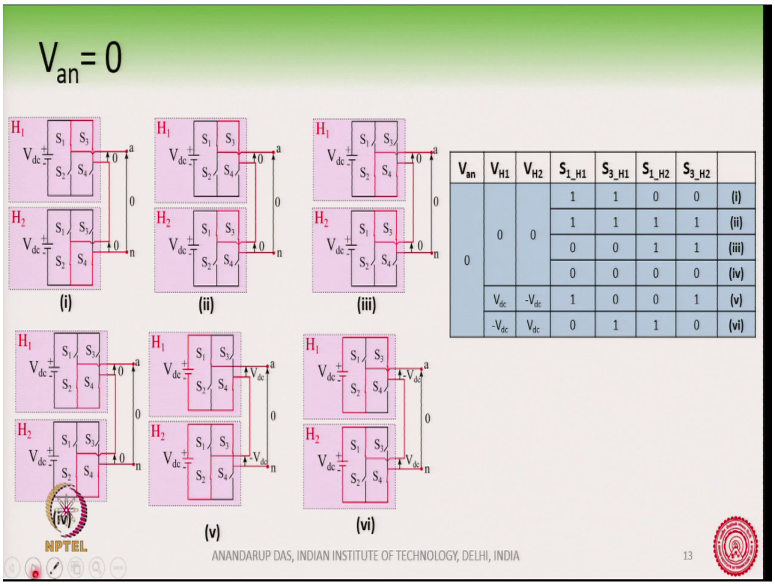
Similarly, if I want to get we can also get V dc by making V H1 as 0 and V H2 is V dc. Of course, V H2 equal to V dc there is only one switching multiplicity possible which is the diagonal element, which is shown here this and this S 1 and S 4 and S 1 and S 4; these are these are turned on. But for getting the 0 from V H1 we have two multiplicities and these are either you turn on S 2 and S 4 or you turn on S 1 and S 3. This is shown here. These are the two multiplicities.

(Refer Slide Time: 23:15)



Again, in a very similar way if we want to get V an equal to minus V dc, then we can have V H1 as minus V dc V H2 0 or we can have V H1 0 V H2 minus V dc right. This is shown here, V H1 minus V dc V H2 0 or V H1 0 and V H2 minus V dc. Sum of both is equal to minus V dc and then, we have similarly four switching multiplicities which can produce this V an equal to minus V dc.

(Refer Slide Time: 23:57)



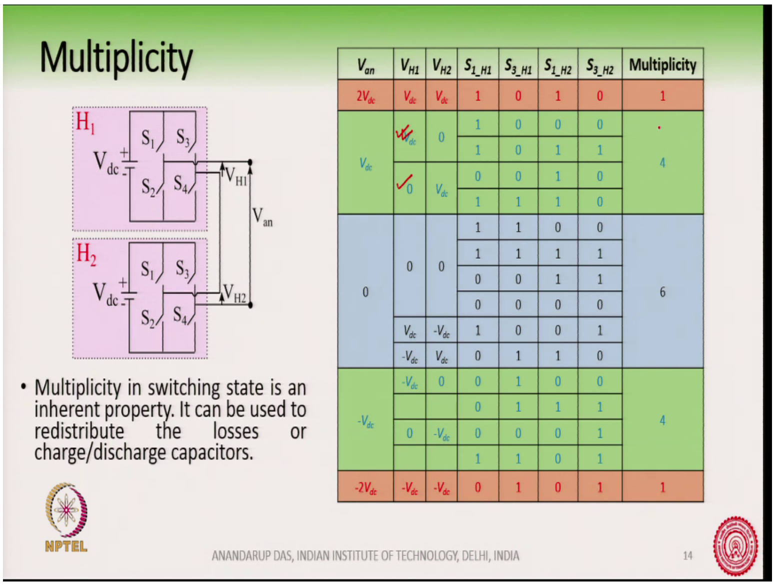
V_{an}	V_{H1}	V_{H2}	S_{1_H1}	S_{3_H1}	S_{1_H2}	S_{3_H2}	
0	0	0	1	1	0	0	(i)
			1	1	1	1	(ii)
			0	0	1	1	(iii)
			0	0	0	0	(iv)
	V_{dc}	$-V_{dc}$	1	0	0	1	(v)
	$-V_{dc}$	V_{dc}	0	1	1	0	(vi)

If we want to get V an equal to 0, then we have even more multiplicities. See if you want to get V an equal to 0, we can have V an equal to sorry V H1 0 V H2 0, we can have V H1 V dc V H2 as minus V dc because the sum of these two will be equal to 0 and we can also have V H1 minus V dc and V H2 as plus V dc again, the sum of these two is equal to 0.

So, now if we see this combination, if we see that V H1 we want to get V dc, we have only one multiplicity that is this 1 0 0 1 which I think is this figure here ok. We have connected the diagonal this diagonal and this diagonal and you see that the voltage produced by H 1 is opposing the voltage produced by H 2 ok. One of one of the H 1 is producing plus V dc, while H 2 is producing minus V dc and they are opposing each other so that the net voltage V an is equal to 0.

Similarly, this sixth combination which is shown here H 1 produces minus V dc and H 2 produces plus V dc and they are their total is equal to 0. Now, for the 0 0 combination when both V H1 and V H2 are producing 0 and the sum is also 0 and then, for the 0 combination we have two multiplicities and those multiplicities are elaborated in the table and also in the circuit.

(Refer Slide Time: 26:05)



V_{an}	V_{H1}	V_{H2}	S_{1_H1}	S_{3_H1}	S_{1_H2}	S_{3_H2}	Multiplicity
$2V_{dc}$	V_{dc}	V_{dc}	1	0	1	0	1
V_{dc}	V_{dc}	0	1	0	0	0	4
			1	0	1	1	
	0	V_{dc}	0	0	1	0	
			1	1	1	0	
0	0	0	1	1	0	0	6
			1	1	1	1	
			0	0	1	1	
			0	0	0	0	
	V_{dc}	$-V_{dc}$	1	0	0	1	
	$-V_{dc}$	V_{dc}	0	1	1	0	
$-V_{dc}$	$-V_{dc}$	0	0	1	0	0	4
			0	1	1	1	
	0	$-V_{dc}$	0	0	0	1	
			1	1	0	1	
$-2V_{dc}$	$-V_{dc}$	$-V_{dc}$	0	1	0	1	1

So, summarizing these multiplicities, we can see that this is the table which is summarizing with all these multiplicities. When we have 2 V dc, when we have V an equal to 2 V dc, we have only one possible switching state. That is therefore, there is only one possibility and this is one multiplicity. When we have when we want to produce V an as V dc, then we have 4 multiplicity as possible that is 4 switching combinations possible. When we have V an equal to

0, there are 6 multiplicities. When we have V an equal to minus V dc, then we have 4 multiplicities and when we have V an equal to minus 2 V dc's, we have only one possibility.

Now, so, we see that when we have when we are going with the higher voltage, we have less multiplicity; when we are going towards 0 voltage, then we have more multiplicities. Why are these multiplicity is useful? These multiplicities are useful in a variety of situation. For example, you may think like that suppose here we have shown these DC buses as stiff DC sources, suppose they are made up of capacitors ok.

For example, we are connecting this cascaded H-bridge converter in a STATCOM application, where we are only injecting reactive power for example, in a transmission line. Then, we have capacitors and these capacitors will continuously charge or discharge. Now, these multiplicities can be used there to charge or discharge the capacitors or it can bypass. For example, suppose we have we take this example; V an is equal to V dc, we would like to get V an equal to V dc.

Now, you see that in one case V H1 is V dc and in other case V H1 is 0. Now, if you have V H1 as V dc, if you have V H1 is equal to V dc this means that this diagonal switches are on which means that suppose this is a capacitor, this is made up of capacitor the capacitor is present in the circuit. The current will flow, the load current will because the diagonal switches are on. So, the load current will for example, if it is coming like this it will come here go like this, go through the capacitor and come out like this, if the load current is going in.

On the other hand, if the load current is going out, then it will come through here, go through this switch, go through the capacitor and go out like this. So, depending on the direction of the load current whether it is going in or going out, the capacitor charge can be changed or the voltage on the capacitor can be changed. But on the other hand, if I use this multiplicity instead of this plus V dc multiplicity, if I use this one then, I can completely bypass the capacitor because when we are getting 0 voltage essentially, we are turning on either the lower two switches or upper two switches. So, which means that the current will come here, we will go through this switch and will come out like this without changing the voltage of the capacitor. It will not go through the capacitor.

So, if we see for example. If you want if the capacitor voltage is going up and I see that I have two multiplicities in my hand to produce the same voltage V dc from the converter. Then, I know that the direction of the current is such that it will further increase the voltage on the capacitor because at that point of time suppose the direction of current flowing into the cell is such that it will further increase the voltage on the capacitor, it will inject more charge into the capacitor.

Then, in that case I will use this multiplicity instead of this multiplicity, I will choose this one. Because in that case I am able to bypass the capacitor so that the voltage and the capacitor is not further increased the reverse is also true. Suppose, I am in a situation where I am saying that the capacitor voltage is going down and I want to immediately charge the capacitor and I see that ok; that means, that at that point of time the direction of current is such that if I choose this multiplicity, then I will be able to charge up the capacitor quite quickly. I will choose that one instead of the second one.

So, therefore, this multiplicity can be used to balance the capacitor voltages. For example, if it is a STATCOM application. For other applications you can also redistribute the losses in the cells ok. So, you can control the rise of temperature and the losses you can redistribute the losses. For example, if you are in a zero state you have several switching multiplicities possible and by effectively using them, you can make sure that all the cells in this H-bridge or cascade H-bridge have equal temperature rise ok.

This is an important criteria because these cells are all modular in nature, you can understand from the from the circuit diagram itself that the cells are modular in nature and when we say it is modular in nature, it means that they have identical construction including the construction of heatsink. So, they have identical gate driver board identical for example, rectifier or capacitors and identical heatsink an identical enclosure and everything. They are all modular and identical.

So, when we put many of these cells and they are when they are working together, you do not want one cell to be heated up very high as compared to the other cells which are much cooler ok. Then, this because then that cell will be stressed more its temperature will rise more and again the longevity will go down. So, it is important that with such converters the loss distribution is also uniform for each cell, it is equal in all the cells. So, this can be achieved by rotating this pattern through the multiplicity ok. So, there also multiplicity plays a role.