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

Lecture – 14
Cascaded H-bridge Converters: Phase-shifted PWM

So, hello everyone, today we will continue with the lectures on Multilevel Converters with Cascaded H-bridge Converter as our focus of study.

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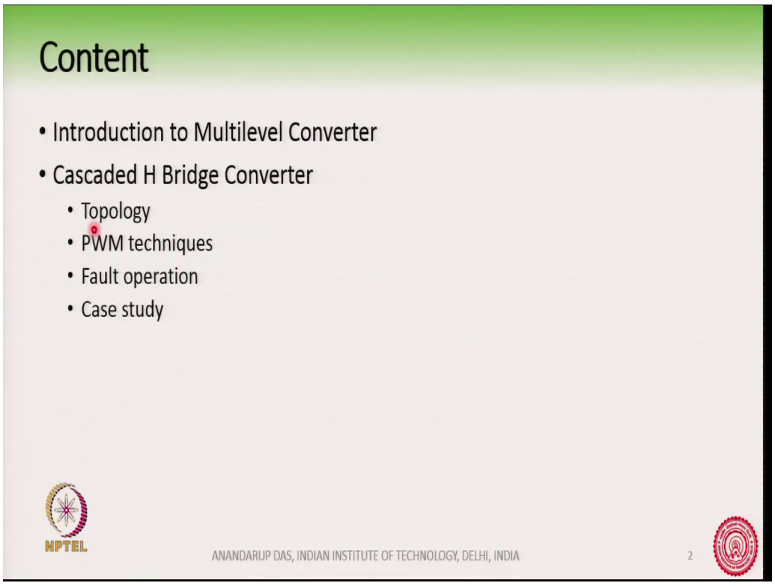

In the last class, we had introduced the topology of the cascaded H-bridge converter and we saw that the H-bridges can be connected in series and thereby we get a number of levels on the output voltage and which we saw that it will become closer and closer towards a sine wave which we wish to generate from the converter. Now, today we will talk about the PWM techniques on cascaded H-bridge converter.

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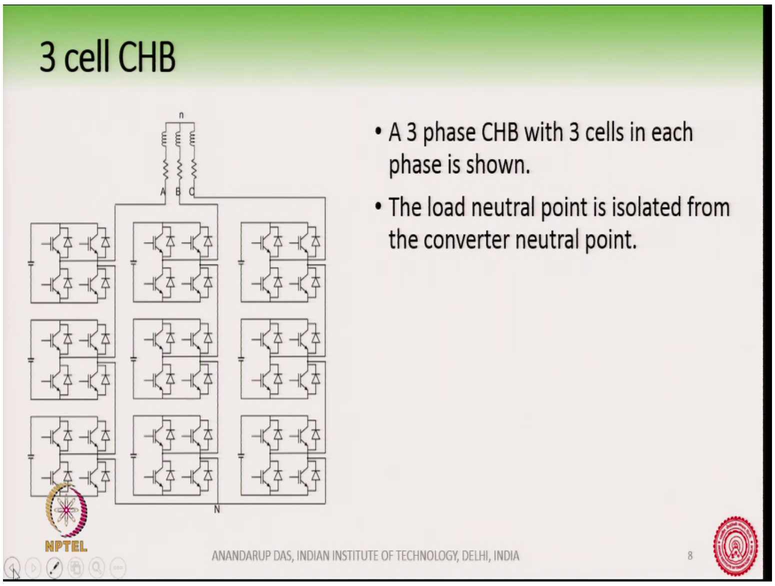

So, if we quickly go over we will this is one 3 cell CHB, the full converter, where there are three cells in each leg and there are three phases.

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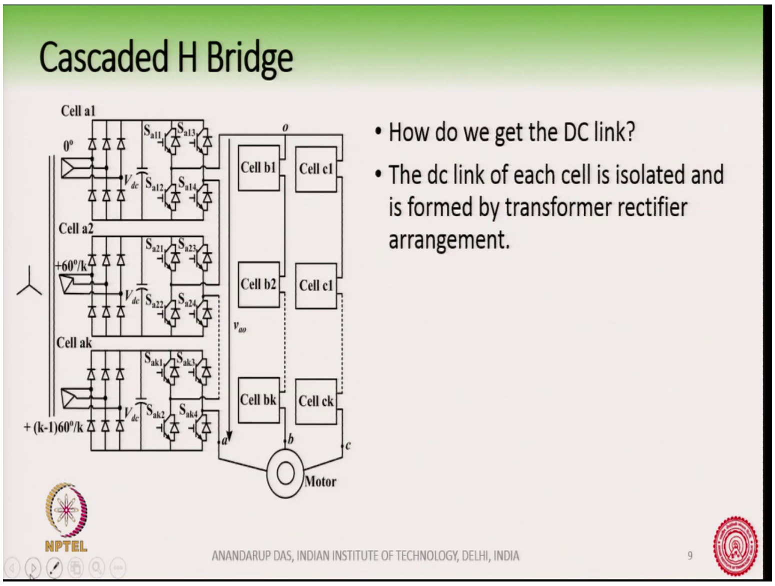

And, yeah this is a more closer representation of how the converter looks like where we have shown how the DC bus is formed.

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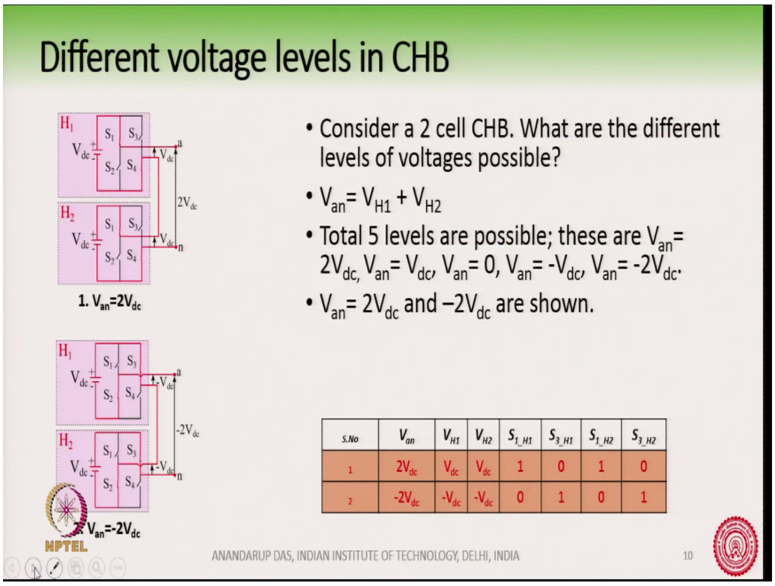

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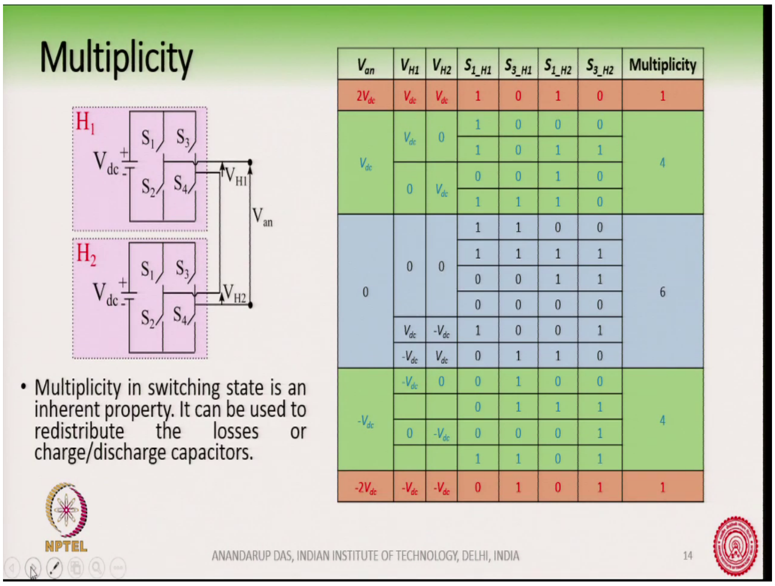

V_{an}	V_{H1}	V_{H2}	S_{1_H1}	S_{3_H1}	S_{1_H2}	S_{3_H2}	Multiplicity
$2V_{dc}$	V_{dc}	V_{dc}	1	0	1	0	1
V_{dc}	V_{dc}	0	1	0	0	0	4
			1	0	1	1	
	0	V_{dc}	0	0	1	0	
			1	1	1	0	
0	0	0	1	1	0	0	6
			1	1	1	1	
			0	0	1	1	
			0	0	0	0	
	V_{dc}	$-V_{dc}$	1	0	0	1	
	$-V_{dc}$	V_{dc}	0	1	1	0	
$-V_{dc}$	$-V_{dc}$	0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

And, then there are these different types of levels and how they are generated using different combinations of switches and we also talked about the multiplicity of switch.

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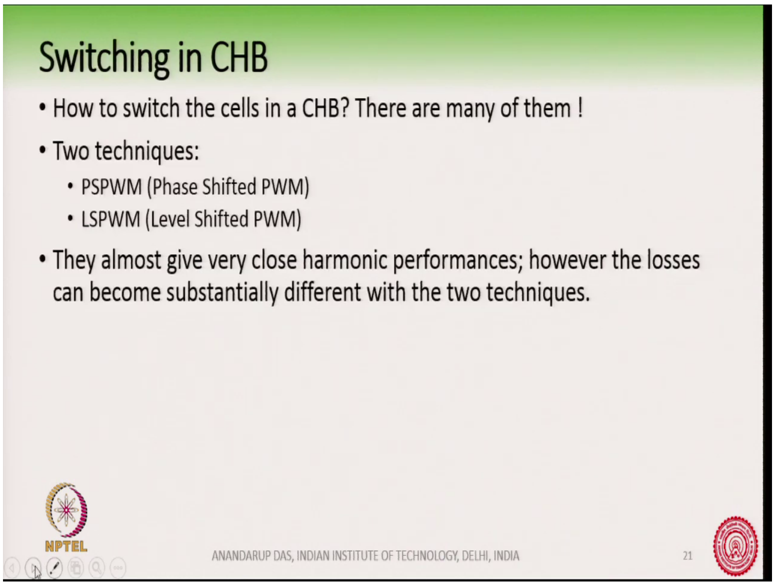

Let us come to the point where we will start talking about PWM in cascaded H-bridge converter. Now, as you have already noticed there are a large number of switches in cascaded H-bridge converter. So, the natural question is how do we switch them? There are so many switches many of them. How do we accurately switch them in order to get the desired waveform ok. So, because each cell there may be many cells in each leg one leg there will be three legs – a phase, b phase, c phase.

So, there are three legs or three phases and in each leg or phase we can have many cells and in each cell there are four switches. So, you can imagine the large number of switches we need to switch from for this converter. So, how do we do that? In order to do that we use two techniques phase shifted PWM and level shifted PWM as you can see here PSPWM and LSPWM.

We can also use a modified space vector PWM where we ensure that the three nearest vectors in a multi level space vector diagram will be switched. When you understand this phase shift PWM and level shift PWM you will yourself understand that it is possible to progress using these PWM techniques for a general in level space vector diagram. It is just a modification of this PSPWM and LSPWM that you we can use a space vector PWM. So, it is the modification is quite simple you center the zero vector for any n level space vector diagram.

Now, focus on these two techniques phase shifted PWM and level shifted PWM basically both these techniques are very similar it is just how the approach is a little bit different. So, their harmonic performances are also very similar, level shift PWM gives a slightly better harmonic performance however, for any level like more than five levels this hardly matters.

So, the performance with phase shift PWM and level shift PWM is almost same in terms of harmonic performances, although LSPWM is slightly better, but the losses if you use these two PWM techniques the losses can become substantially different with the two techniques. In fact, for level shift PWM the loss distribution will get highly unequal or uneven and there are techniques again to counter or to rectify this uneven loss distribution, we will see that.

But, let us first see what is the general approach for PWM by taking a very simple example. So, when we talk about phase shift PWM or when we talk about level shift PWM, let us see what is the main or basic idea.

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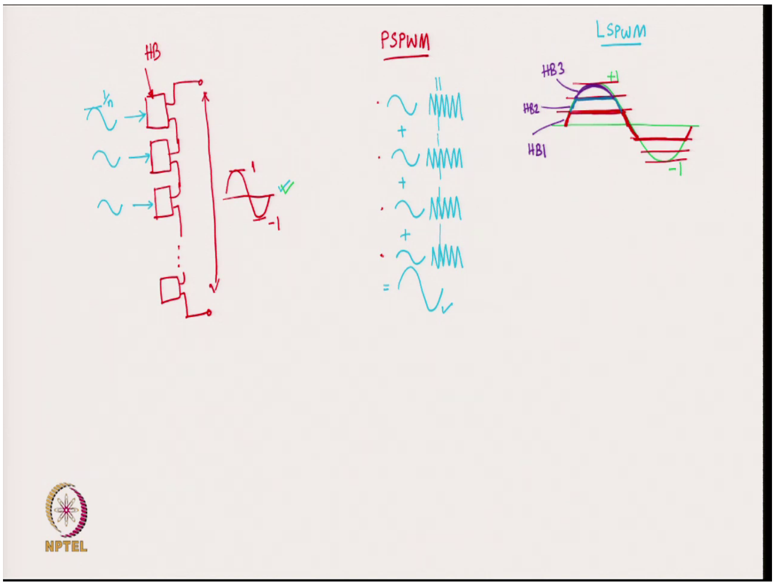

So, here you can consider suppose we have a large number of H-bridges like this. So, each is an H-bridge here and we have cascaded them in series. So, what do we want? So, there may be many such them here. So, what do we want out of this? So, here at the output we would like to have a sine wave. A large magnitude probably in the range of several kilovolts or hundreds of kilovolts we want a sinusoidal output here.

Now, how do we get that sine wave? The phase shift PWM; the phase shift PWM does that very easily by asking each of this H-bridges to produce 1 by n times the amplitude of the sine wave. So, for example, if this sine wave has an amplitude between 1 and minus 1 per unit then in phase shift PWM what do we do? We basically ask each of these H-bridges each of them to produce an identical sine wave like the one we want to produce here all of them are identical, but each having 1 by n times the amplitude of the big sine wave; that means, where n is the number of H-bridges.

So, that means, each H-bridge is as if taking up the responsibility of producing 1 by n so that we have the output of the first H-bridge as this one, the second one is identical to it, the third one is identical to it and the fourth one is identical to it like that, so that we at the end get a big sine wave which is this waveform here. So, each H-bridge is like producing one by n times the amplitude of the required waveform at the output. However, while doing so, of course, how will it do this? It will do this by comparing this sine wave with a high frequency triangle ok. So, this has a triangle, this has a triangle, this has a triangle and this has also triangle.

So, the trick here in phase shift PWM is that there is a slight phase shift. So, if you draw this one there will be a slight phase shift between the carriers and that slight phase shift causes the first band of harmonics to shift more and more towards the higher side in the harmonic spectrum. So, the fundamental voltage produced by each H-bridge is 1 by n times what is required, but and they are produced using or comparing this modulating waveform with the high frequency triangle or carrier.

But, the carrier for the H-bridge 1 and for H-bridge 2, for H-bridge 3 these carriers are slightly phase shifted that is why the term phase shift PWM. These carriers are slightly phase shifted from each other so that the resultant waveform that is this one here this resultant waveform is actually getting rid of many of the harmonics, we will see that which how the harmonics are getting shifted we will take an example.

Now, what happens in level shift PWM? Now, if you see the level shift PWM; the level shift PWM in this again we would like to produce this big sine wave right this big sine wave of 1 and minus 1 here. Now, in level shift PWM what we do is partition the waveform like this in such a way that say for example, H-bridge one produces this part of the waveform only this part; this part of the waveform is produced by the first H-bridge and the rest of the time it can be fully turned on I mean it is just holding the voltage.

The H-bridge 2 can build up over it and can produce this part of the waveform and hold the voltage like this here. H-bridge 3 can do or produce this part of the waveform. So, you can see that in level shift PWM each H-bridge is taking up the responsibility to produce a part of the waveform say here this one for example, can be. So, this H-bridge the red part is produced by the H-bridge one the blue part of the waveform is produced by H-bridge 2 and this violet part can be produced by H-bridge 3 and so on ok. Of course, I have not shown the negative side actually the negative side is also present.

So, H-bridge 1 is actually probably producing this part of the waveform. So, in phase shift PWM the waveform produced by all the cells are identical ok. You can see here this, this, this, this all the H-bridges are producing an identical output waveform which are just getting summed up and producing the output high voltage sine wave whereas in case of level shift PWM this is not the case.

In level shift PWM each H-bridge is taking one part of the waveform it is producing one part of the waveform. So, H-bridge 1 is producing one part, H-bridge 2 is producing one part H-bridge 3 and so on producing some portions of the waveform so that at the end the overall sine wave is produced. So, this is the basic idea about phase shift PWM and level shift PWM and keeping this in mind we can go ahead and study these two techniques in detail.

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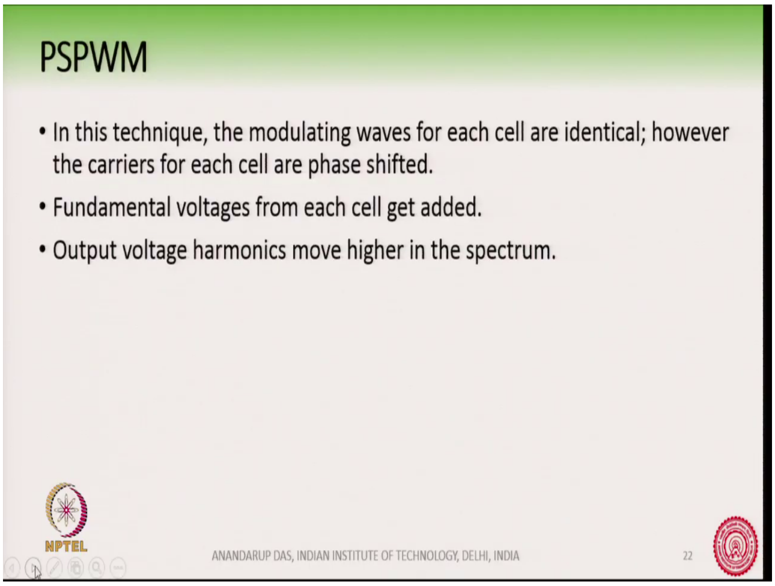

Phase shift PWM; so, as I told you the modulating waves for each cell are identical here, but the carriers are getting slightly phase shifted in case of phase shift PWM. The fundamental voltage so, since the modulating waveform is same for all the cells. So, the fundamental voltage produced the magnitude of the fundamental voltage produced from each cell is also same and they are getting added up because the cells are them themselves connected in cascade serial serially connected. And, what happens with the harmonics? The harmonics move towards the right or higher in the harmonic spectrum.

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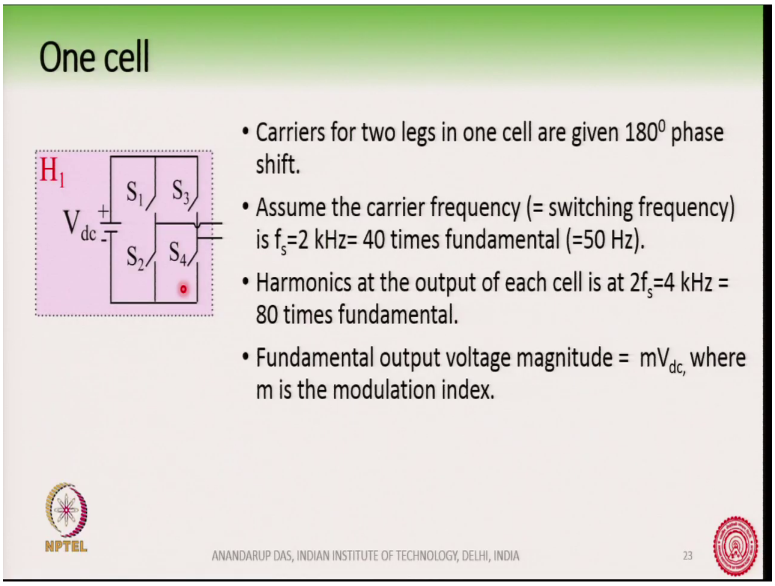

So, in order to understand this technique we will take we will go through an example ok. Let us take an example and we will understand it this phase shift PWM technique through an example. So, for phase shift PWM let us start with one cell ok. So, this is one cell here and as we have also seen earlier that the output of for the output voltage from one cell, what we can do is that the carriers for the two legs in one cell are given 180 degree phase shift which means that the carriers for S 1 and S 2 and the carriers for S 3 and S 4 are given 180 degree phase shift.

Earlier, when I was talking about the operation of H-bridge we had shown that the modulating waveform for the two legs were 180 degree phase shifted. Here we are saying that the carriers are 180 degree phase shifted, it gives the similar performance. So, carriers for two legs in one cell are given 180 degree phase shift.

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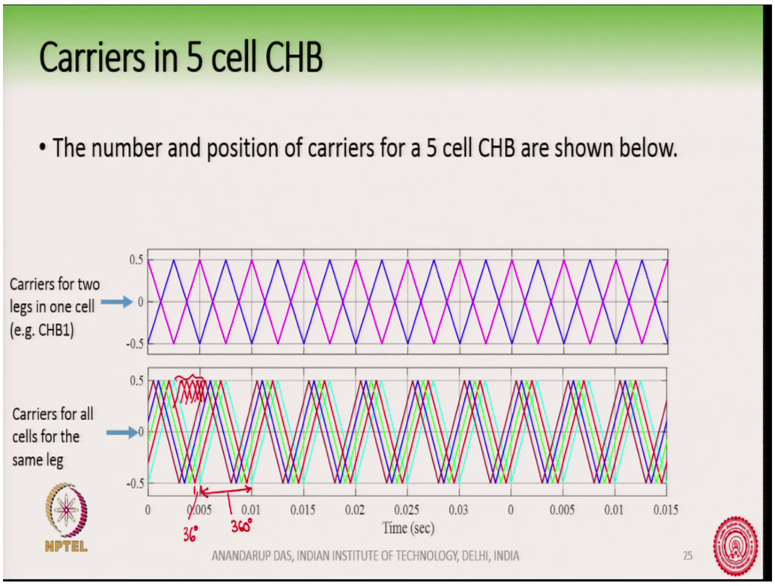

So, let us see how the carriers look like, this is an example. You see the carrier for example, the left leg is this blue one and the carrier for the right leg is the pink one ok. So, they are 180 degree phase shifted S 1 and S 2 are complementary S 3 and S 4 are complementary, if we do not do that then we are going to sort the DC bus.

Now, assume the carrier frequency is equal to 2 kilo Hertz and if the fundamental frequency is taken as 50 hertz; fundamental frequency means fundamental voltage frequency which needs to be produced from the output of the converter. So, if that voltage is say 50 Hertz, then we are taking like 40 times the carrier frequencies 40 times the fundamental.

Now, of course, we understand that carrier frequency should be equal to switching frequency right this we have seen because whenever the modulating waveform is crossing the carrier each time the transition happens so, there will be one switch turning on and another will be turning off. So, the carrier frequency is equal to switching frequency of the device. So, what happens with the harmonics at the output of each cell now the carrier frequency is f s and which is governing this one leg here similarly another carrier frequencies governing S 3 and S 4; the switching frequency is equal to carrier frequency.

The output of one cell, that is here, this output. This output here if we see the harmonics at the output we find that it is at 2f s which is equal to 4 kilo Hertz or 80 times the fundamental frequency for 50 Hertz frequency. So, the each cell is switching at f s whereas, the output if you see the harmonic spectrum the out the first band of harmonics at the output voltage here will be at 2f s this happens because the two carriers are 180 degree phase shifted.

And, what is the fundamental output voltage magnitude from one cell? It is equal to mV dc, where m is the modulation index it can be taken very close to 1, we may also add a third harmonic here when we work with isolated neutrals. So, mV dc it can go up to 1.15 mV dc if we add a third harmonic or something like a max min algorithm which we have earlier discussed where we add the triple n harmonics.

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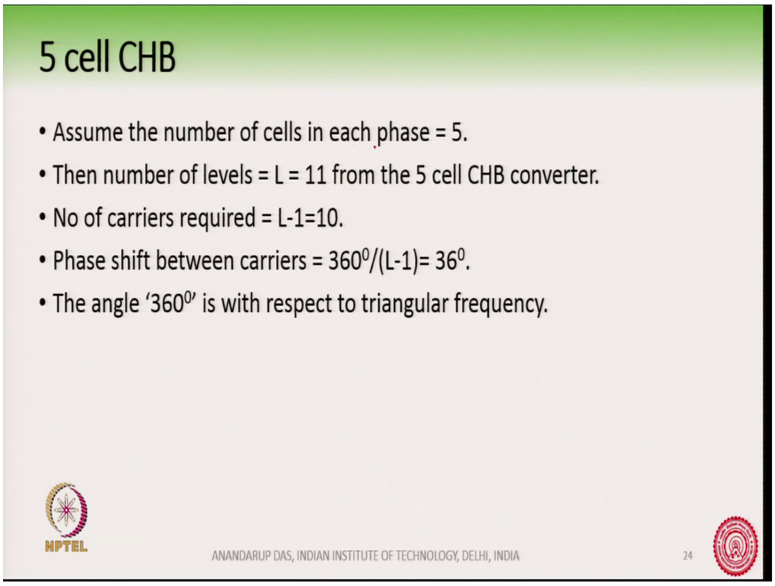

Let us assume that there are five cells in the CHB and we are applying phase shifted PWM. So, assume the number of cells in each phase is equal to 5 and then total number of levels which is possible from this converter is 11; that is 2 n plus 1, where n is the number of level cells. So, for this case as I had earlier told all the cells will required their own carriers ok, but each carrier is shifted phase shifted from each other.

So, how many carriers do we require here? We will require L minus 1 that is 10 carriers here, where the phase shift between the carriers is 360 degree divided by L minus 1 that is equal to 36 degree ok. So, this is the phase shift which is required between the carriers it is equal to 360 degree divided by L minus 1 which is equal to 36 degree. Now, this angle of 360 degree is with respect to the carrier or the triangle frequency we must keep this in mind. So, let us see what is what I am talking about here.

See for example, carrier for lets for if there is one cell then, this are the carriers for the two legs of one cell left leg and right leg and they are 180 degree phase shifted. Now, if we think about the left leg alone for all the 5 cells only the left leg then you see these five carrier wave forms which are shown here of different colors these are the carriers required for the 5 for the legs left leg of the 5 cells. You can clearly see that these carriers are slightly phase shifted from each other. You can see here these are slightly phase shift there is a phase shift here there is a slight phase shift.

How much is the phase shift? This phase shift is 36 degree; this phase shift is 36 degree were 360 degree is this duration. So, that is what I was saying that the 360 degree is with respect to or in the domain of the carrier frequency. So, if this is the 360 degree, then the difference between carriers is 36 degree as you can see in this diagram below. So, these are the carriers for all the cells in the same leg ok. So, these are the say left leg, these are the carriers ok.

For the right leg for all the 5 cells we will also have 5 similar set of carriers again shifted by 36 degree from each other, so that we will this part which you are seeing empty here this part will be filled up by the five carriers of the right leg of 5 cells ok. So, this part here you will see there will be one more carrier 2, 3, 4, 5 like this the five carriers will come here which we are not showing because the picture will get clumsy. So, I have not shown that. So, I will just remember it exists here I have not shown it. In fact, I will erase it here and I will only show you the 5 carriers for the 5 cells only the left leg or maybe the right leg ok.

So, this the important thing to note here is if this is 360 degree here that is 360 degree in the carrier frequency, then this angle is 36 degree and how do we get that? We get that from this formula ok. So, for a 5 cell CHB we need 10 carriers this because it is an 11 level converter, we will need 10 carriers and the phase shift between carriers is always 360 degree divided by L minus 1 that is 36 degree and these are the waveforms.

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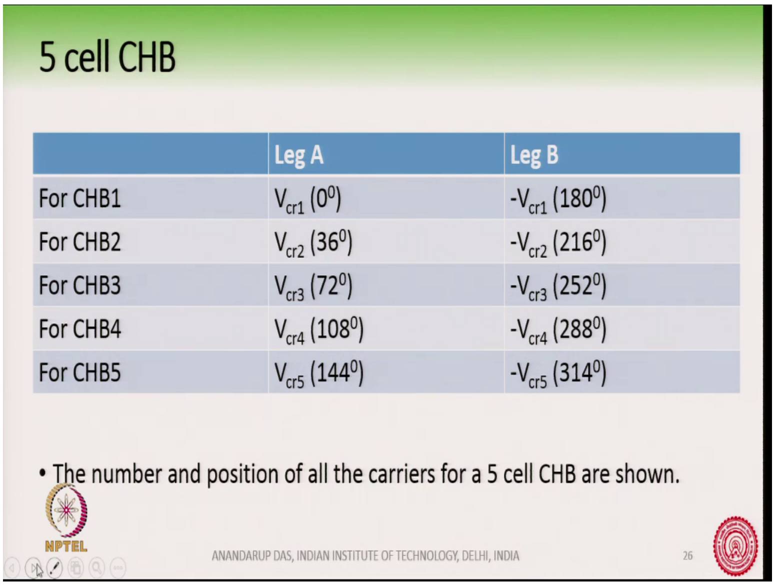

So, how these 5 cell CHB how does the carriers actually sit? So, for so, there are the five cells CHB 1, 2, 3, 4, 5 and for one CHB1 leg A is suppose the carrier is 0 degree. Of course, leg B is 180 degree as you can you have seen here for example, this is leg A the blue one is leg A, the pink one will be leg B ok. So, these are the two carriers for the cell 1. V cr 1 is 0 degree and for leg B it is minus V cr 1 180 degree.

For CHB 2 of course, the leg A CHB 2 is shifted by 36 degree as we had earlier discussed. So, V cr 2 is 36 degree and for leg B again this will be 180 degree plus 36 degree which is equal to 216 degree. For CHB 3 it is 36 degree plus 36 degree that is 72 degrees and for leg B it will be 216 plus 36 which is 252 degrees.

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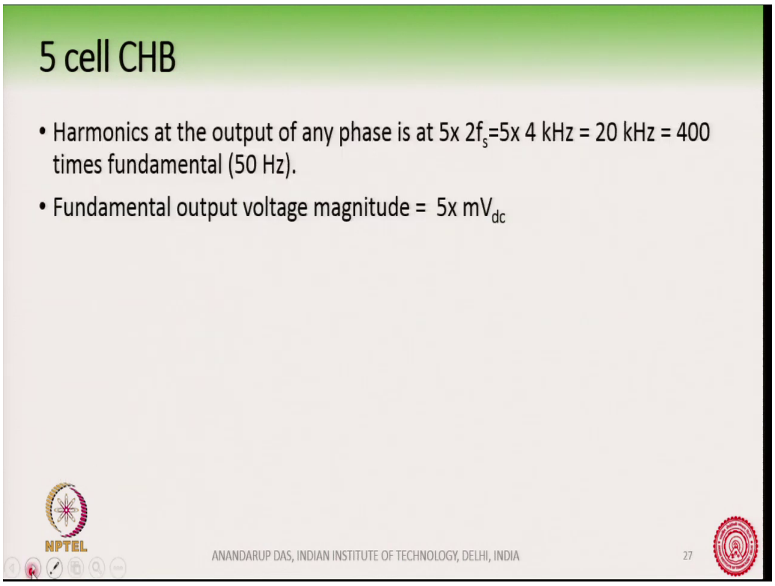

So, this is the place this is the point where the carrier starts that is these angles are this is the point. So, if suppose say this is 0 this is 0 degree then this is 36, 72 like that this is the place where the carrier will start and so on. So, for the 5 CHB cells, so, you can see how the carriers are positioned in leg A and leg B.

Now, what do we if we do this carrier shifting, but this is what phase shifted PWM means. Phase shift your carriers what happens really is that we had earlier seen that the harmonics at the output voltage of one cell was at 2f s ok, where f s was the switching frequency of any device and is equal to the carrier frequency. So, if there are five such cells then the harmonics the first band of harmonics will reside at 5 into the output of one cell that is 5 into 2f s which is equal to 5 into 4 kilo Hertz which is equal to 20 kilo Hertz or 400 times the fundamental.

So, this is the advantage of shifting the carriers that now at the output we are going to see the voltage the voltage waveform where we if we do this harmonic analysis of that voltage waveform there is a fundamental and nothing in between and the first band of harmonics only resides at 400 times the fundamental nothing in between, no harmonics. So, of course, therefore, what happens is the output voltage is very close to a sine wave we will see one example ok. So, this harmonic from the harmonic point of view this is very much advantageous.

And, of course, the fundamental output voltage magnitude because it is serially connected the fundamentals get added and so, the output from the 5 cell h CHB will be 5 times mV dc where mV dc is the output of one cell.

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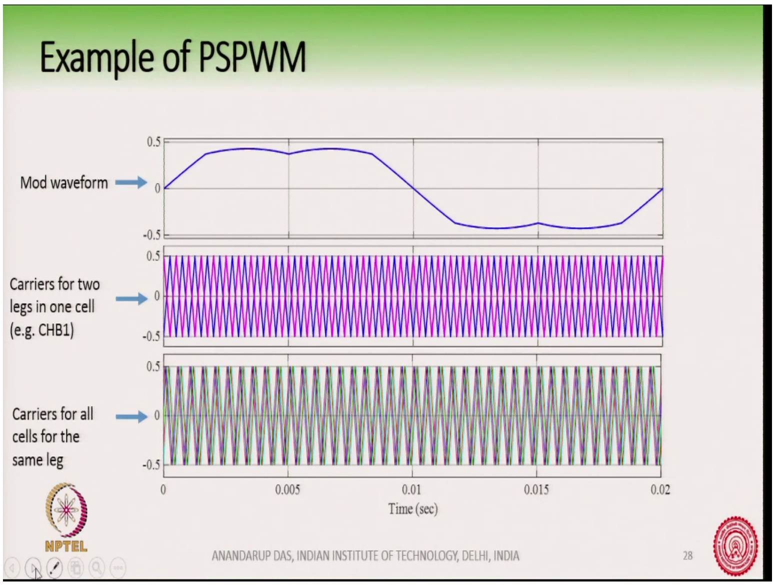

So, yeah so, this is what the one example you see that this is for example, the modulating waveform. This is the 50 Hertz the sine wave here the fundamental sine wave here is having the 50 Hertz component of course, I have we have added a third or a triplen harmonic here by using this mean max algorithm so that we get maximum dc bus utilization. So, the waveform has this two bulges here which correspond to the addition of the triple n harmonics.

And, then this is the carrier for one cell CHB1 and carrier for all the same legs ah, these two waveforms we have seen earlier. Now, I include this waveform to show that the carrier frequency is much higher than the fundamental frequency ok.

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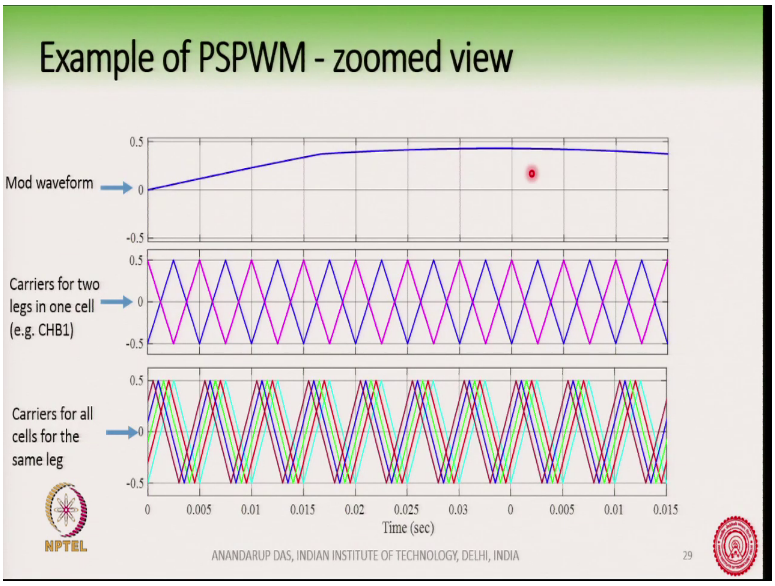

And, if you zoom in so, zoom in on a particular section of the modulating wave form you can distinctly see how the carriers here and here they are they are aligned with each other.

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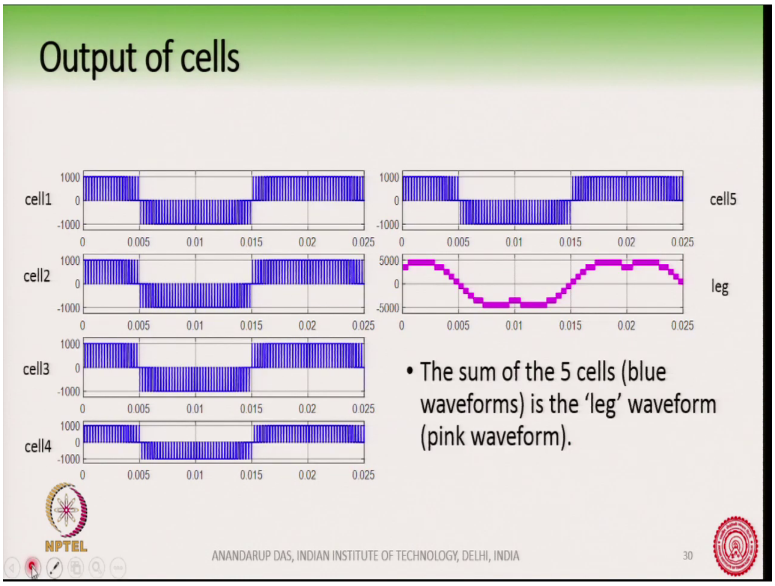

So, let us see how is the; so this is a simulation. So, we have taken 5 cell CHB with each cell having 1000 volt DC bus and so, the output of cell one. So, each of these cells are given the same modulating waveform. Remember, each of this cell is given the same modulating waveform they are all having the same modulating waveform, but their carriers are slightly phase shifted.

So, if they are giving the same modulating waveform the fundamental voltage produced from each cell is same and so, this waveforms here all these five blue waveforms are almost identical. In fact, you cannot distinguish by seeing this waveforms you cannot really differentiate whether they are different at all, but actually what is the difference here? The difference is that because of the carriers are slightly phase shifted these five waveforms are slightly phase shifted from each other very slightly that 36 degree which we had earlier discussed.

Slight phase shift is there which causes so, when we sum them when we add them together which is happening in the cascaded H-bridge we get to this waveform here this waveform here the pink one. So, this is the output is the pole voltage or the output of the whole that pole voltage or the leg voltage this is the output. And, you can see this output is pretty much closer to a sine wave because now you see these are the these are the steps in the waveform or the levels in the waveform and it is much it is very close to the original modulating waveform. Remember, the original modulating waveform along with the triplen harmonic is this one and you see the actual waveform is also going closer and closer to that ok. It will even become even closer if the number of cells increases ok.

Now, remember this phase shift had actually caused this waveform to appear like this if there was no phase shift between cell 1, cell 2, cell 3, cell 4, cell 5 what we would have got? We would have got this particular waveform, but 5 times it is amplitude if there was no phase shift; if the all the waveforms were identical because the modulating wave is identical and all the carriers are also identical we would have got this waveform, but 5 times its amplitude they would have just added up because of the phase shift now we get this waveform here ok.

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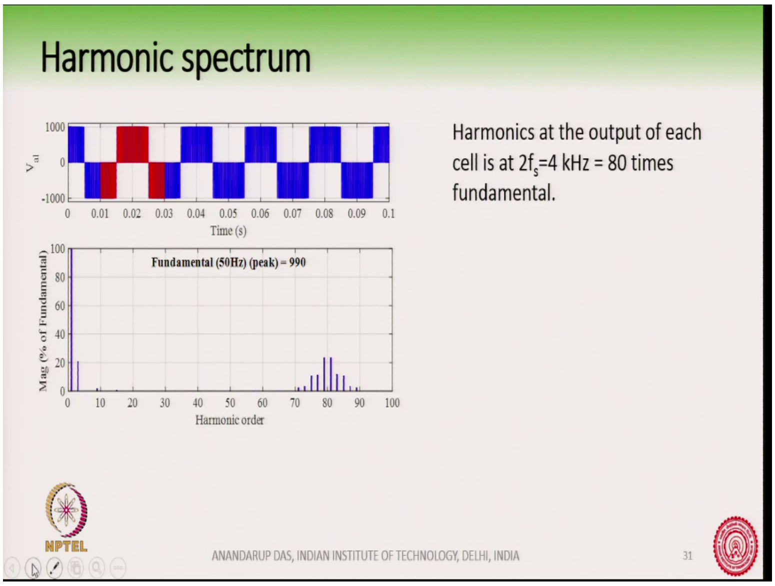

So, quickly we can see the harmonic spectrum. So, this is the output of one cell you can see this is from 1000 to minus 1000 because the DC bus is taken as 1000 volt and you see this is the output the modulation index was taken as 0.99. So, the peak voltage is 99 mV dc that is 990 volt and you see the this is the fundamental here and there is a third harmonic here there is a third harmonic. So, these are the third, ninth, fifteenth harmonic here because of the max min algorithm.

So, third, fifth, ninth is there, but the first band of harmonics is residing around 80 because we have kept 2f s equal to 4 kilo Hertz ok. So, the first band of harmonics is residing around 80 times the fundamental, this is the output from one cell.

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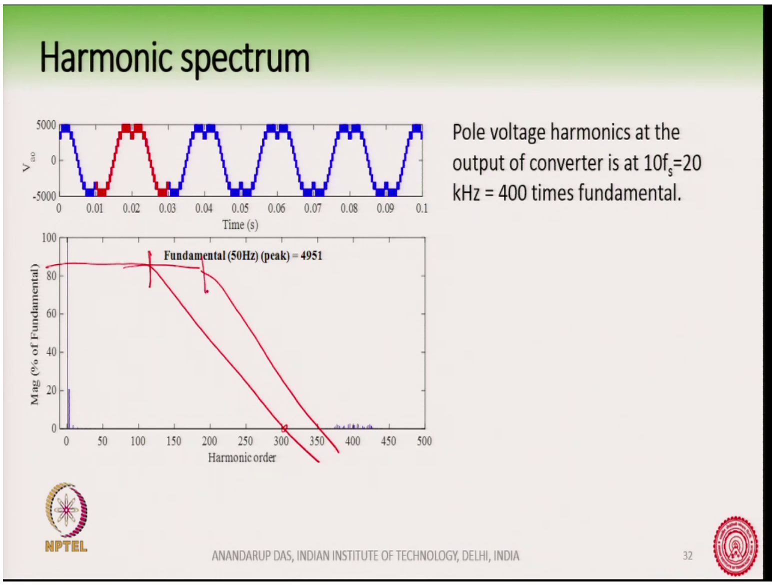

Now, when we see the output of the 5 cells together it is like this waveform. This is the pole voltage harmonics. Interestingly you see this has the third harmonic same as before here and the fundamental 50 Hertz peak is now 4951 which is 5 almost 5 times the 990 volts which we had earlier the last slide. So, it is 5 times the fundamental is increased.

The third harmonics again get added up third, 9, 15 all are present, but you see there is now there is no harmonics around 80. There is no harmonics around 80, it has disappeared. No harmonics around 80, 160 or even 240 like that, no harmonics there and the whole set of harmonics the first band comes around 400, here this is the first band of harmonics with a very small amplitude. And, this is around like 20 kilo Hertz or 400 times the fundamental and this is what the phase shifted PWM technique has done. It has shifted this 80, it has this harmonics around 80 all of them have shifted to 400 ok.

Of course, this is very easy why this is easy it is very easy to design any filter because anyway because I mean you can design the filter with a cut off frequency like this ok. So, the corner frequency is here and the gain of the filter is kind of like 0, even before the 400 harmonic comes. So, the even you can go up to like this is a second order filter. So, the corner frequency can be suitably chosen higher so that the size of the filter goes down, anyway.

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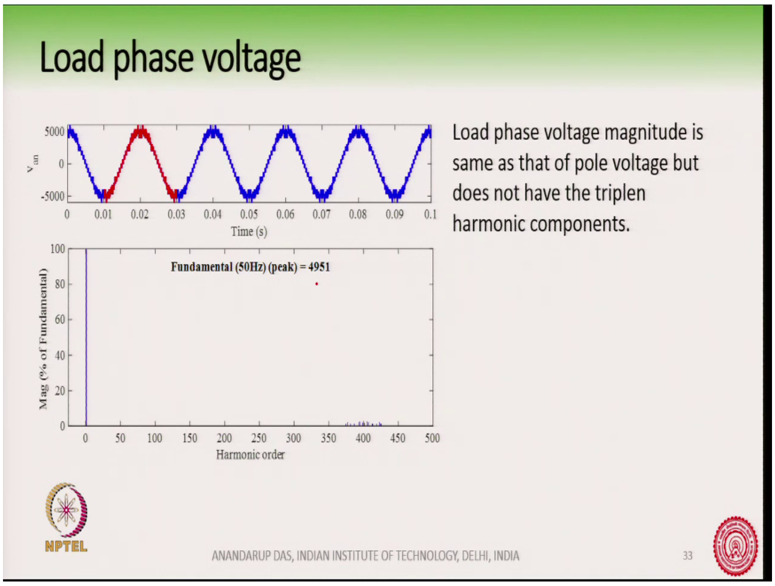

So, the phase voltage; phase voltage waveform looks like this and you see the third harmonic have disappeared in the phase voltage and this is expected because the line voltage cannot have the third harmonic, and the load phase voltage also cannot have the third harmonic. So, the third harmonic helps in there or the triplen harmonics helps in better dc bus utilization and the fundamental voltage is 4951 available on the load which is same as what is available from the pole and the harmonics are around 400 ok.

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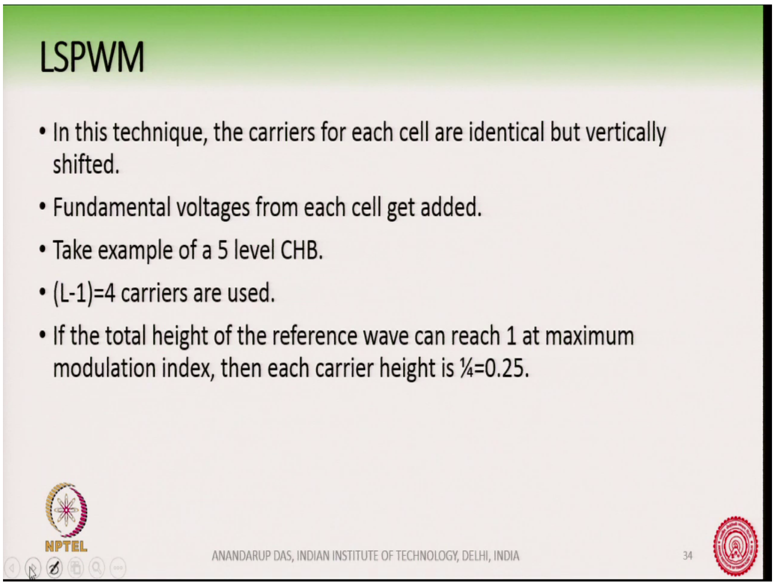

And, similarly, you can also draw the line voltage waveform.