High Power Multilevel Converters - Analysis, Design and Operational Issues
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Lecture – 08
Space Vector PWM – Switching sequence

So, we continue our discussions with Space Vector PWM.

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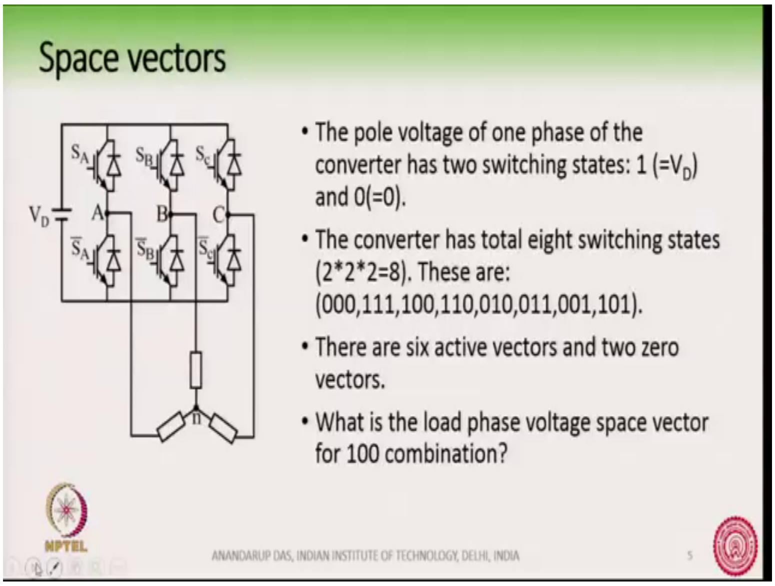

So, far we have seen what is a space vector and space vectors can also be realized using the graphical way and we have seen the space vector of the pole voltage.

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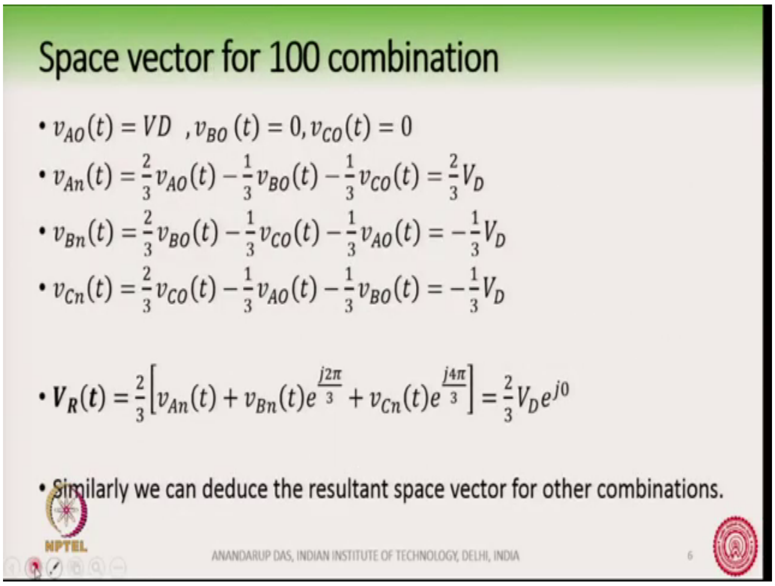

And from which we can derive the space vector of the phase voltages.

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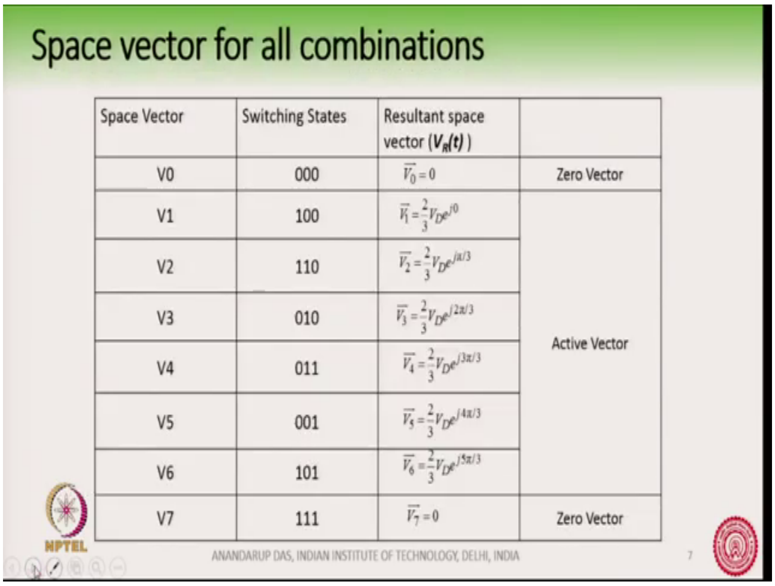

Space Vector	Switching States	Resultant space vector ($V_R(t)$)	
V0	000	$\vec{V_0}=0$	Zero Vector
V1	100	$\vec{V_1}=\frac{2}{3}V_D e^{j0}$	Active Vector
V2	110	$\vec{V_2}=\frac{2}{3}V_D e^{j\pi/3}$	
V3	010	$\vec{V_3}=\frac{2}{3}V_D e^{j2\pi/3}$	
V4	011	$\vec{V_4}=\frac{2}{3}V_D e^{j3\pi/3}$	
V5	001	$\vec{V_5}=\frac{2}{3}V_D e^{j4\pi/3}$	
V6	101	$\vec{V_6}=\frac{2}{3}V_D e^{j5\pi/3}$	
V7	111	$\vec{V_7}=0$	Zero Vector

And these are the space vectors for; there are 8 space vectors for the convertor three phase two level converter.

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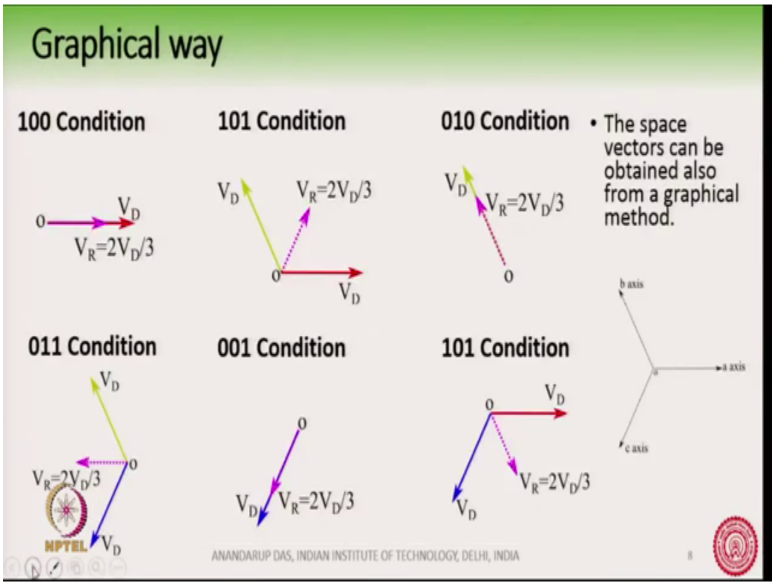

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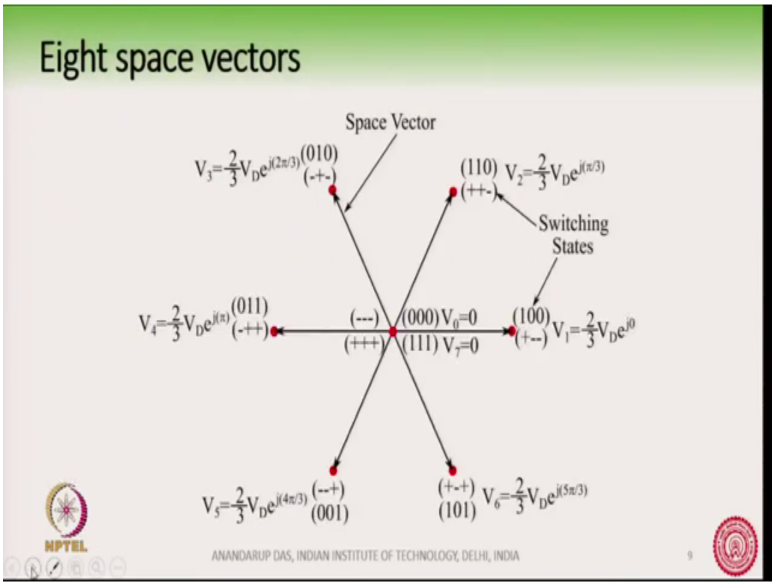

There are 8 space vectors as you can see on this slide and these 8 space vectors are denoted by these red colored dots and there are 6 such vectors and there are 2 vectors here at the central position and the because they are vectors they are indicated by arrows ok.

So, in this diagram there are altogether 6 active vectors which are at the corner of an imaginary hexagon and there are 2 zero vectors which are situated at the center of this hexagon. The magnitude of this vectors are all same that is why it is a regular hexagon. So, the magnitude is two-third V D and the 6 sides, they are making an angle of 60 degree. The switching state we have so far denoted the switching states by 1 0 0 or 1 1 0 or 0 1 0, an alternative way of denoting the switching states is plus minus minus or plus plus minus, minus plus minus like that.

Here this plus minus minus corresponds to like 1 representing plus and 0 representing minus and here also 0 representing minus. So, this is an alternative way of representing the space vector diagram switching states. There are of course, minus minus minus and plus plus plus corresponding to 0 0 0 and 1 1 1 these are producing the zero vectors. So, these 8 space vectors are basically forming the boundary of an imaginary hexagon ok, which is shown by the dotted line in this figure.

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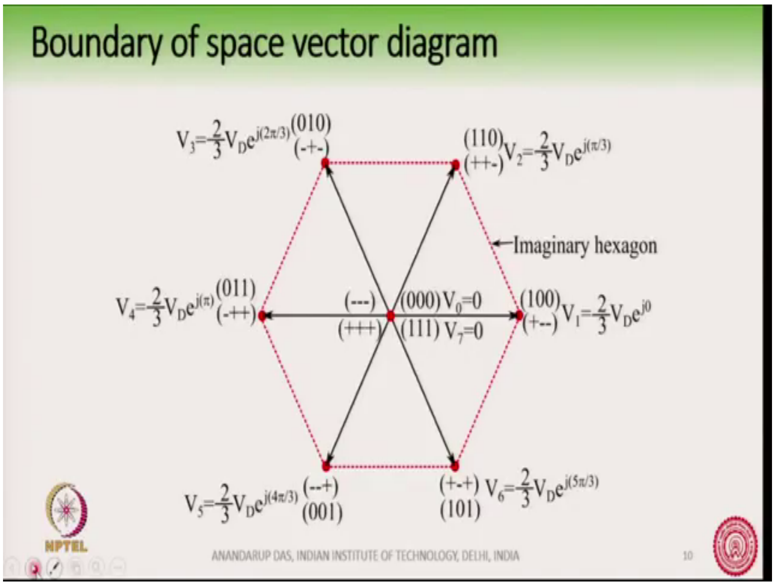

The hexagon is imaginary. So, there are in this diagram, there are only 8 vectors, but for the sake of understanding and for the sake of easy implementation of space vector PWM, we can think of the boundary as an hexagon. Of course, this is imaginary.

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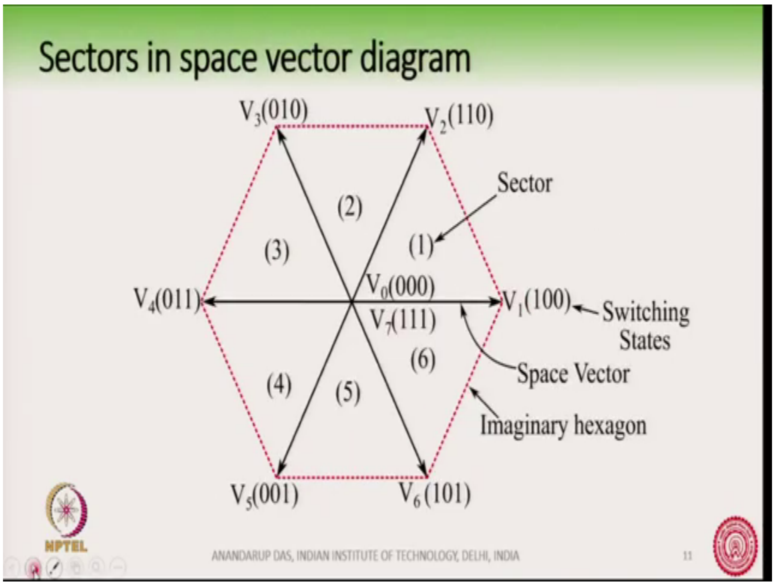

So, once we have made this boundary, once we have drawn this boundary, we can now divide the whole hexagon into 6 sectors ok. These sectors are 1, 2, 3, 4, 5, 6 as you can see in this diagram. The sectors are triangular in nature the reference vector at any point here can be realized by switching the three nearest vectors in the same sector where the reference vector lies ok. This we have seen now what is the maximum voltage?

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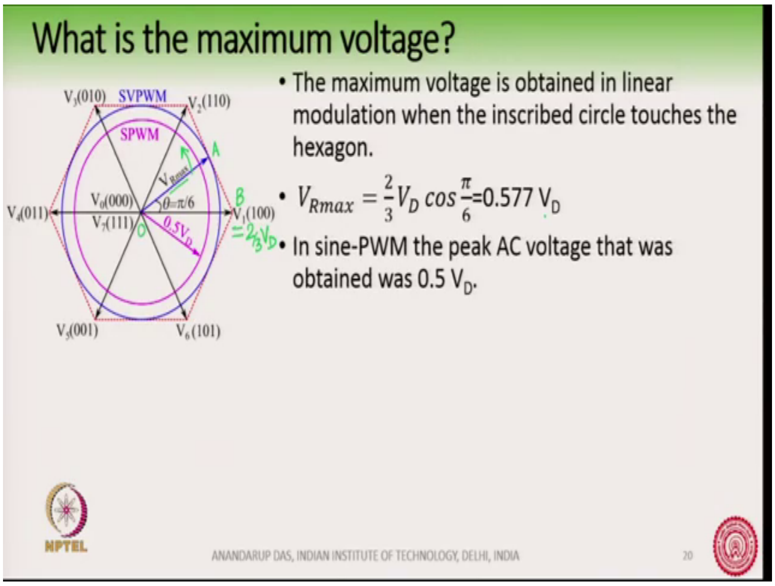

The maximum voltage can be obtained by observing the space vector diagram and the resultant vector which is inside this space vector diagram..

So, you can see here we have seen that the resultant space vector is a vector which is rotating. For example, this is a resultant vector here and it is rotating. So, what is the length or what is the maximum length of this resultant vector? The maximum length of the resultant vector or the reference vector is obtained when this resultant vector corresponds to the maximum or the biggest circle which can be inscribed inside the hexagon. This blue colored circle is the biggest circle that can be inscribed inside the hexagon.

So, what is its magnitude? The magnitude can be easily obtained by observing that the side of the hexagon is equal to two-third V D and this triangle here this triangle here, in this triangle say I give the name O A B. In this triangle, O A B, the angle A O B is pi by 6 ok. So, therefore, the length of the side O A is equal to O B into cos 30 degree; that means, it is equal to two-third V D into cos 30 degree which is shown here two-third V D into cos pi by 6 which is equal to 0.577 V D. So, the length of the vector V Rmax is equal to 0.577 V D, where the length of the vector V 1 equal to the vector O B is equal to two-third V D.

So, the maximum voltage that can be obtained in space vector PWM is equal to 0.577 V D. We can compare this with the sine PWM technique and in sine PWM technique, we found out that the peak AC voltage that could have been obtained was 0.5 V D, where the sine wave was touching the height of the carrier. As soon as the sine wave was touching the height of the carrier, we say that we are reaching the end of the linear modulation and that magnitude was 0.5 V D because the sine wave can touch up to V D by 2 to minus V D by 2.

So, it was 0.5 V D or V D by 2. So, compared to that the space vector PWM gives us 0.577 V D ok. This is the maximum voltage we can get and that can be impressed on the load. So, load peak phase voltage is 0.577 V D and this is about 15 percent more than what can be obtained with sine PWM. So, sine PWM is obtained 0.5 V D and in space vector, we have obtained 0.577 V D. So, which means we are obtaining 15 percent more in space vector PWM from the same DC bus voltage. So, this is the advantage of using space vector PWM.

And we it is we have earlier seen that by introduction of third harmonic, we can also get 15 percent more and in space vector also we get 15 percent more. So, from the point of view of DC bus utilization, both the third harmonic addition and the space vector PWM are same. They give the same DC bus utilization. However, the harmonic performance of space vector PWM is better. People generally prefer the space vector PWM. Now, as you may have realized that although space vector PWM gives us 15 percent more utilization as compared to sine wave; but it involves substantial calculation.

For example, we have to first identify where is the reference vector, whether it is lying in sector 1, sector 2, sector 3 etcetera. Then, corresponding to that sector, we must have a table a kind of a lookup table or something similar to that where we can say that ok, in this sector these are the three nearest vectors and then, we have to make the timing calculations the formula that we have seen T 1, T 2 and T 0. We have to calculate those formulas and then, we have to do the actual switching on the converters.

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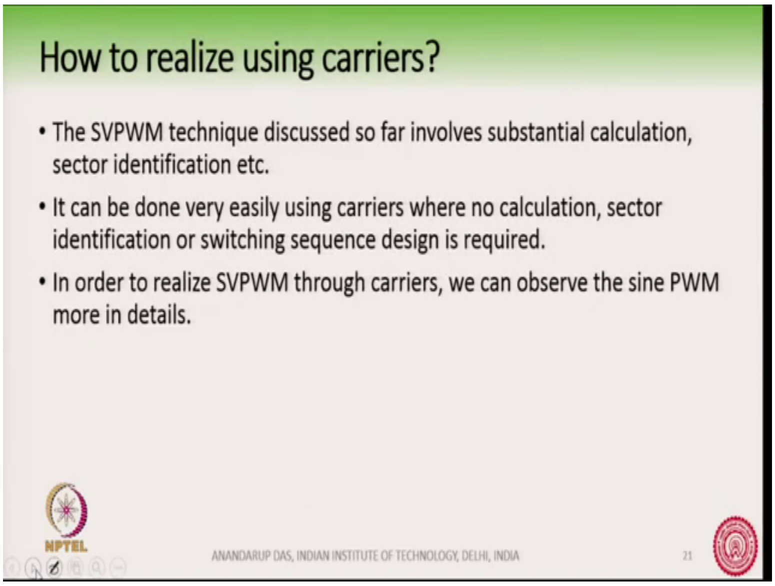

So, the space vector PWM technique which we have discussed so far involves substantial calculation. But initially the space vector PWM when it was implemented was done in this fashion only, which involved a lot of calculation. But later, it was realized that it can also be done using carriers like what we do in sine PWM, exactly like that. Space vector PWM can also be realized using the same carrier based approach like sine PWM and that made life a lot easier because then, we do not require any calculation any sector identification or switching sequence design etcetera.

So, we can say that after this carrier based implementation of space vector PWM, we have made the space vector PWM and extension of the sine PWM. Now, in order to realize this space vector PWM through carriers, we first observe the sine PWM, now in more in details. So, what happens in sine PWM?

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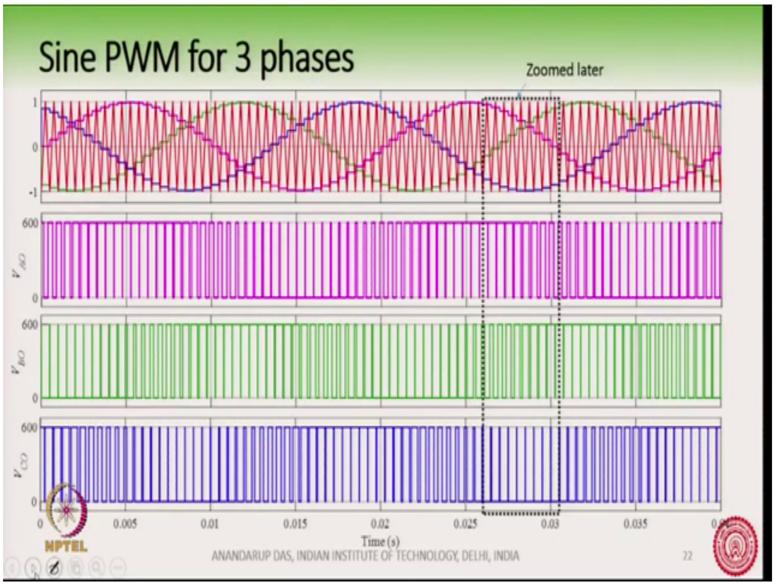

So, here on this diagram, we are showing the sine PWM, where you can see the high frequency carrier here and three sine waves three modulating sine waves balanced that corresponds to v A v Band v C. And then, we also have shown the pole voltages v AO v BO and v CO which is which are fluctuating between 0 and 600 Volt; the DC bus being 600 Volts. Now, let us zoom into this portion of the waveform. Let us zoom in here and show it in the next screen.

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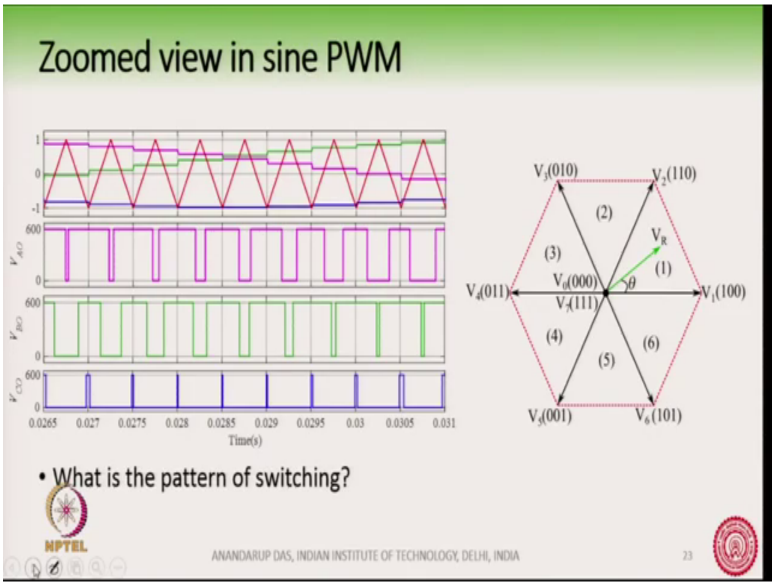

So, this is the zoomed version. Now, let us try to see the pattern of switching. Let us try to see the pattern of switching in this zoomed view.

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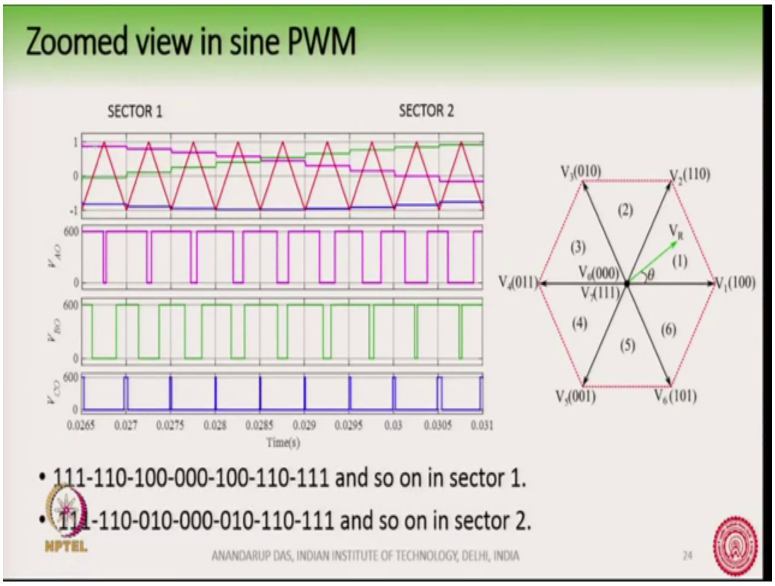

Let us concentrate here. Let us concentrate first in the first carrier that is we are first seeing here. How do you see the pattern of switching? The carrier is here and we are following the logic that if the modulating or the reference wave is more than the triangular wave, then we make the switch upper switch on so that we get the full DC bus voltage. When the modulating wave is less than the triangular wave, then the lower switch is turned on and we get 0 voltage.

So, the modulating waveform for A phase is this pink waveform here. The modulating waveform for B phase is the green one here and that of the blue one here is the C phase. So, you see here that v AO is high up to this point and then, it goes low because the modulating waveform is the modulating waveform is smaller than the carrier in this area.

So, therefore, we have got a notch here going to 0; the rest of the time v AO is high. Similarly, v BO, v B O is high up to the point here. Up to the point here v BO is high and then, it goes low during this region as shown here and then again, got it goes high like this and v CO you can see that it goes it is low throughout this period and is high for the rest of the period, you can follow the pattern throughout.

Now, then what is the pattern of switching? What is the pattern of switching? If you see observe the first region here we see that all three phases are 1. So, therefore, the first switching state is 1 1 1; after that C phase goes to 0, while A and B phase are 1. So, we have a switching state 1 1 0; afterwards in this area, in this area we have B and C phases going to 0, where as A phase is 1. So, we should have a switching state 1 0 0 and then, here we have a A phase, B phase and C phase all three going to zero. So, therefore, we have 0 0 0 here ok.

After this A phase goes up, while B and C phases are still down. So, therefore, we should have 1 0 0 and then, we have a 1 1 0 here; that is here 1 1 0 and then, you have a 1 1 1 where all three phases have gone to 1 that is 1 1 1 and so on in sector 1. So, it will again repeat for the next carrier and subsequently the other carriers. So, we see that in sine PWM also, in sine PWM also we have a switching sequence, which is similar to that of space vector PWM ok. You see that this actually is in sector 1. The switching is happening in sector 1 and you see if you observe the switching sequence, so we have started from 1 1 1 and then, go on to 1 1 0, 1 0 0 and 0 0 0 and then, again going back 1 0 0, 1 1 0 and then 1 1 1.

So, basically we are switching in sector 1 here and the switching sequence of going from. So, there is only 1 switch which is changing at each switching change; only one phase is changing its state other two are remaining constant. So, the switching sequence here is very similar to the switching sequence in space vector PWM.

You can take any other sector for example. We can take sector 2. Sector 2 somewhere is for example here and you can again confirm that the switching sequence here. In sector 2 in sine PWM is very similar to the switching sequence of space vector PWM in sector 2. So, we see that there is a substantial similarity between how the switching sequence progresses in sine PWM as well as in space vector PWM. Let us zoom in further into one carrier. So, which means that let us zoom in further into one carrier inside this carrier alone.

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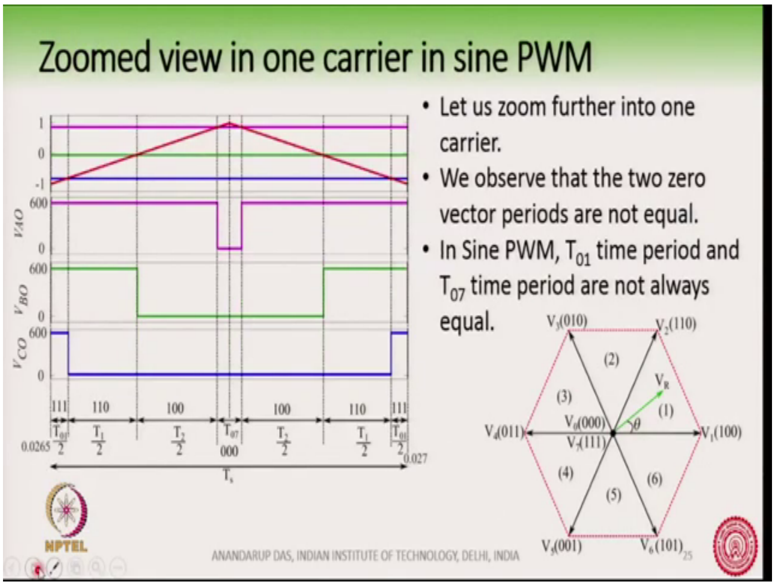

Then, there. So, this is that carrier. This is the carrier there and you have the three modulating wave forms; A phase, B phase and C phase here.

So, the A phase waveform and the C phase waveforms are position in sine PWM; are position in such a way that it is not always that T 01 and T 07 that is the first and the last zero vectors in a cycle, they are always equal. It is not the case in sine PWM. You can you can easily see that because suppose in sine PWM, A phase is reaching the top which means it is close to 1, at that point in a balanced system B and C phases are not at their negative maximum so that the zero vectors that is the 1 1 1 and the 0 0 0, these two vectors in the switching cycle will not be equal ok.

So, this un-equalness of the 2 zero vectors is what makes the difference between sine PWM and space vector PWM. In space vector PWM, the starting and the ending vectors which are the zero vectors are always made equal; whereas, in sine PWM they are not necessarily equal, most of the time they are unequal. So, if. So, this is what you have seen.

So, if sine PWM T 0 1 time period and T 0 7 time period are not always equal. So, this T 0 1 by. So, we have divided into two sub cycles T 01 by 2 and here also T 07 by 2. So, this T 01 by 2 and T 07 by 2, these two lengths are not necessarily equal in sine PWM and that is what makes it different from space vector PWM.