High Power Multilevel Converters - Analysis, Design and Operational Issues
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Lecture – 07
Space Vector PWM – Timing calculation

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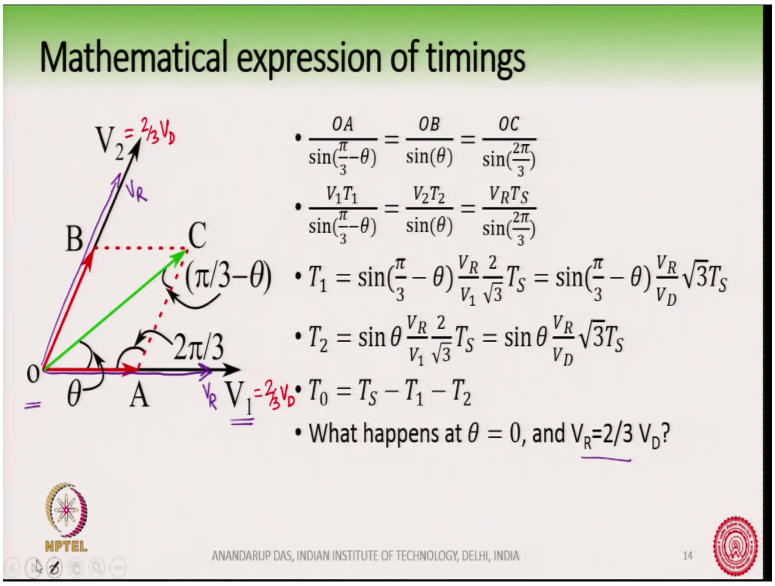

Now, what happens at theta equal to 0? So, once we have seen this formula then we can find out some interesting cases, for example what happens at theta equal to 0? If you put theta equal to 0, then we see that T 2 does not appear. So, what happens at theta equal to 0 is that this vector OC now lies along V 1 vector, right. So, which means that say I can draw this one here, this is the vector V R here, ok.

So, what do we, what do we guess that in order to realize this vector V R we showed only switch V 1 vector and the 0 vector. These are the two vectors we should only switch because this vector is now lying on V 1 axis, we cannot switch the V 2 vector here because as soon as we give a weightage to V 2 then the vector V R will start moving anti-clockwise towards V 2.

So, it is also seen from the equation that at theta equal to 0 T 2 becomes 0, so we should not give any weightage to V 2 vector. And so, the in order to realize this V R we should switch V 1 vector for a large duration of time, but for a certain small duration of time as we see from the length of the V R we should switch the 0 vector, ok. Small duration is a 0 vector and for a large duration the V 1 vector.

In a similar way, if I had a vector which was lying here V R then I should I could I must switch the V 2 vector for a long duration of time and the 0 vector, we should not switch the V 1 vector at all.

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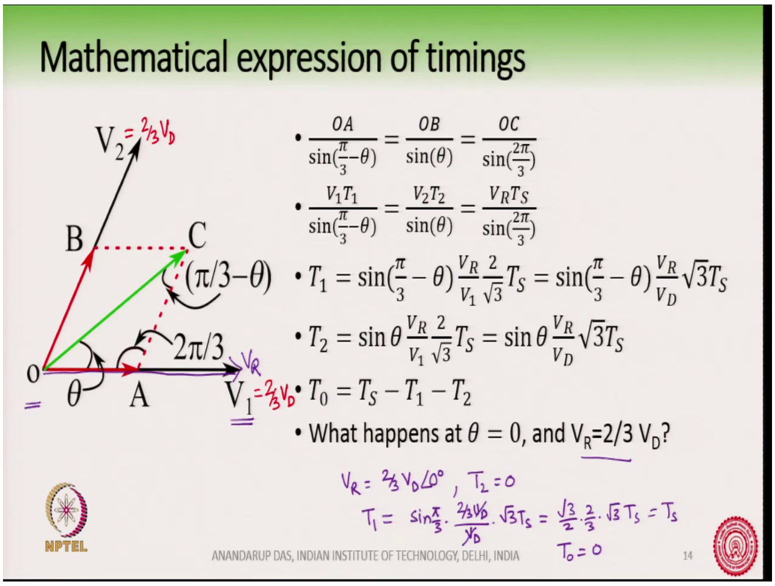

What will happen? Let us take another example, this one. What will happen if V R is equal to two-third V D? Which means that if V R is this one, V this is V R is equal to V 1 is equal to two-third V D. What does it indicate? It indicates that this throughout the T h time period, we should only switch V 1 nothing else, ok. For the whole time period the 100 percent duty or 100 percent of the time period V 1 should be switched and 0 vector or V 2 vector should not be switched and this can also be understood from this T 1, T 2 and T 0 expression.

If you put V R is equal to two-third V D you will find that T 1 is equal to T S and T 2 equal to 0 and T 0 equal to 0, at theta equal to. So, if I, so this can be also understood from this expression that suppose V R is equal if we say V R is equal to two-third V D at angle 0 degree then of course, which means theta equal to 0, so which means T 2 will become equal to 0. And T 1 if you substitute in this equation then we see that T 1 will be equal to sin pi by 3 into two-third V D divided by V D into root 3 into T S. So, this value will be will be root 3 by 2 into 2 by 3 into root 3 and into T S which is equal to T S.

So, therefore, we find that if V R is two-third V D at an angle 0 degree, then T 1 is equal to T S, T 2 equal to 0 and T 0 is definitely therefore will be equal to 0. So, that throughout the time period T h time period only the vector V 1 will be switched, ok.

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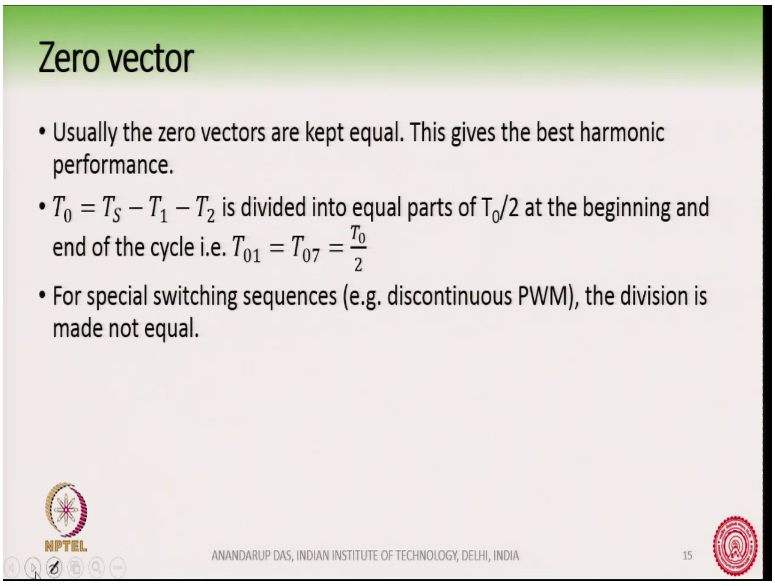

Now, as we had earlier also said the 0 vectors are the V 0 and V 7, ok. They are usually their duration is usually kept equal, ok. It gives the best harmonic performance. So, T 0 by 2, T 01 is equal to T 0 by T 07 is equal to T 0 by 2.

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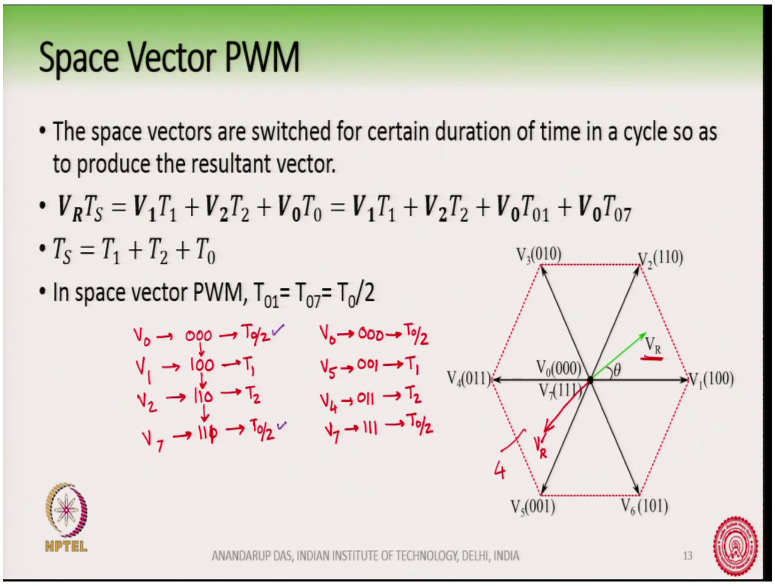

So, here we have seen, we have split V 0 and V 7 into T 0 by 2 and T 0 by 2 in this switching. So, but for some special switching sequences for example, if we have discontinuous PWM, this division is not made equal, ok. And this is done in spite of the fact it will give poorer harmonic performance, but it is done for getting some other benefit. For example, like loss distribution or changing the losses in the switch or say in neutral point clamp converter the capacitor voltage balancing and so on. So, these special switching sequences are used where T 0 the starting and the ending vectors are not of equal duration of time, ok.

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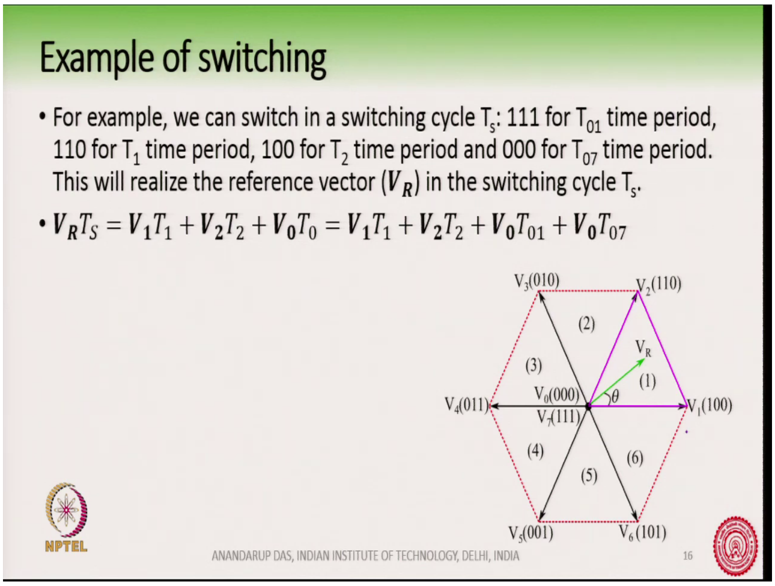

Now, this example we have given in an additional example here that, when we are switching on these 3 vectors we have we are switching 111 for T 01 period, 110 for T 1 time period, 100 for T 2 time period and 000 for T 07 time period, where T 01 is equal to T 07 is equal to T 0 by 2, this we have taken already.

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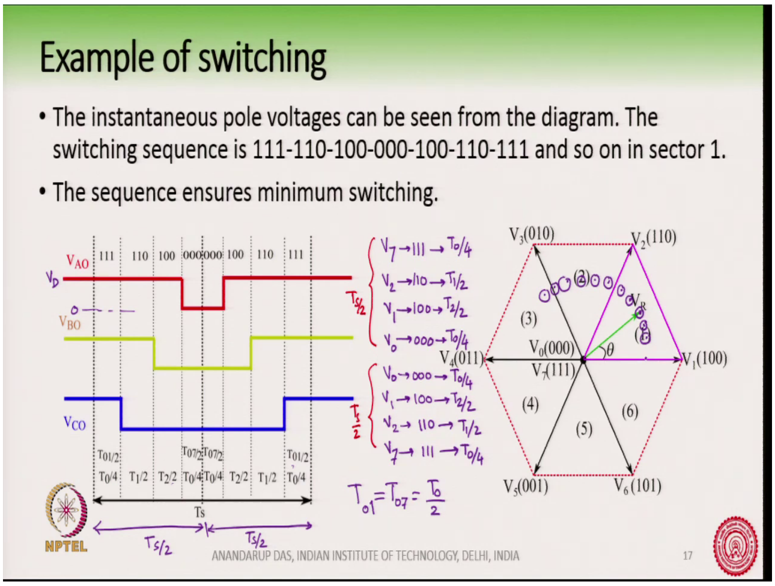

Now, how does the instantaneous pole voltage look like? When I say that we are switching these vectors, for certain duration of time then how will the switching look like? So, here we see a switching sequence, so when we do the switching. So, let us see this switching where we are switching say from 111, 110, 100 and 000, ok. So, this there is a reference vector V R and we are realizing by switching like V 7, V 2, V 1 and V 0, ok. So, V 7 means 111 and then V 2 is 110, and V 1 is 100, and V 0 is 000, ok.

So, if we realize by switching these 4 vectors how will the pole voltage look like. When we have 111 it means that A phase B phase and C phase all 3 are having one state, so which means that if this is 0, this is V D, then V AO, V BO, V CO all 3 are V D during this point of time.

Next is the T 1 time period. Now, here we have actually divided this whole T S time period into two subdivisions, that is T S by 2 and T S by 2. Why we have done this will be clear when we analyze the space vector PWM with implementation using a carrier. As of now we can say that this time period T S is now equally divided into T S by 2 and T S by 2. So, this is the T S by 2 and here is another T S by 2, ok. These are the two subdivisions T S by 2.

Now, in one of the subdivisions T S by 2, so this is the total time period T S and in one of the subdivisions T S by 2 we can switch say V 7, starting from V 7, we can switch V 7 V 2, V 1, V 0. So, this is the T S by 2 time period and for the next T S by 2 time period we again switch V 0, V 2, V 1 V 7, ok. So, we have now divided this T S time period into two parts. So, we have seen that it has been divided into two parts. So, in the first T S by 2 period we will switch from V 7, V 2, V 1 and V 0, and in the next switching interval T S by 2 we are switching V 0, V 1, V 2, V 1, V 7; that means, in the first switching cycle we are going in a clockwise in a clockwise direction and in the second switching cycle we are going in an anti-clockwise direction. Exactly why this is happening can be understood when we are doing the carrier based implementation of SVPWM.

Now, you see here how will the pole voltages look like. The pole voltages for example, in the first interval we have V 7 vector which means we have applied 111. So, during this first T S by 2 period if we see the first interval, the first interval is T 01 divided by 2 because now we have divided the whole T S period into T S by 2 and T S by 2. So, we have now 4 states under 4 timing periods under T S by 2. Those 4 timing periods are T 01 by 2, T 1 by 2, T 2 by 2 and T 07 by 2. And in the second sub cycle T S by 2 we have T 07 by 2, T 2 by 2, T 1 by 2 and T 0 by T 01 by 2. So, basically we have split the whole thing into two parts.

Now, during this of course, here in this example T 01 is equal to T 07, that is what space vector PWM ensures that the 0 vectors are equal. So, in this T S by 2 we see that we have a 0 vector at the start and a 0 vector at the end. Similarly, in the next T S by 2 interval we have a 0 vector at the start and another 0 vector at the end. Both these 0 vectors are equal in duration. In between, we have these two vectors T 1 and T 2 which are the active vectors. So, if you see the pole voltages we can see that 111 you have for one, for the first T 01 by 2 period which is actually equal to T 0 by 4 period because in this example T 01 is equal to T 07 is equal to T 0 by 2, T 01 is equal to T 07 is equal to T 0 by 2. So, therefore, in the first T 0 by 4 time period we have 111; that means, V AO, V BO, V CO all 3 are having a voltage of V D.

In the next timing interval T 1 by 2, so this is the timing interval T 0 by 2 here sorry, T 0 by 4, this is the timing interval here, T 0 by 4, where all of them are 111. In the next timing interval which is T 1 by 2, we have 110. So, you have V AO 1, V BO 1, V CO 0. Then in the subsequent the third one which is for a duration of T 2 by 2 we have 100, which means V AO is 1, V BO is 0, V CO is 0. And in the last one we have 000 which is again for a duration of T 0 by 7, sorry, T 07 divided by 2 which is again T 0 by 4 timing duration we have 000 which means V AO is 0, V BO is 0, V CO is 0.

And next, in the next T S by 2 period this will again get repeated, but it will be in a opposite direction of switching. So, this is T 0 by 4, then we have T 2 by 2, then we have T 1 by 2, then we have T 0 by 4. So, this is how the switching is happening and this is the time duration for which the switching is happening.

We can note several things here. The first thing that we note is that this kind of switching is ensuring that at whenever there is a switching transition; that means, whenever V AO or V BO or V CO is going from 0 to V D or V D to 0, whenever there is such a switching transition then only one phase is having that, ok. So, here you can see that initially all 3 phases are having V D voltage here and only C phase goes down, while A and B phase is maintaining the voltage. Again, here at this instant B phase is going down while A phase is at V D voltage, so which is evident from this 111, 110, 100, and 000, this switching sequence ensures that there is minimum transition happening and that minimum transition is only one out of the 3 phases is doing a transition.

Now, another thing that is important here is the switching the frequency of the phase. So, the switching frequency is defined as the time for which the switch is turned, so it is a total time period for which the switch is first turned on, it turns off and again turned on, ok. So, this is called the switching frequency. So, here we see that the A phase, if you see the A phase here it was, so this is during the entire T S time period we see that A phase it was turned on here, I mean turned on means the upper switch was turned on and then the upper switch is turned off here, the lower switch is turned on here and then the upper switch is again turned on, ok. So, therefore, the upper switch as well as the lower switch because they are complementary in nature, the upper switch is turned on and off once in this whole time period T S, which means the switching frequency of the upper and the lower switches in phase A is equal to 1 by T S, ok.

Similarly, if you see B phase, the upper switch in B phase is turned on here, it is turned off here remains turned off throughout this time and then again turns on here the upper switch in B phase. So, it means that the upper switch in B phase is switching once in this whole time period T S. So, it has a switching frequency which is equal to 1 by T S.

Similarly V CO, so both the devices in each leg have a switching frequency which is equal to 1 by T S, ok. So, T S is we can all, we also say that T S is the sampling period. Where is that sampling comes from that will see when we go into the carrier based PWM. But during this time period T S where we are trying to realize the reference vector V R, that time period T S or this is inversely equal to the switching frequency of the devices. So, higher is the switching frequency it means lower is the time T S or vice versa, higher is the time T S lower will be the switching frequency of the devices, ok.

So, when you say that this was the timing durations to realize the vector V R for, so this were the, so we can say that V R this was the vector which we want to realize. In the next time interval we can realize a vector reference vector here, in the subsequent here like this. So, this is how the reference vector is moving in a circle. So, at each point of time we are basically sampling the reference vector and then having a switching like this and trying to realize that V R vector, the reference vector, ok.

The reference vector is rotating for example, in a circle. So, this is the voltage which is getting impressed on the load, ok. The load phase space vector, load phase voltage space vector is this V R which is rotating in a circle and we are trying to realize this one using these for each time we are using this samples here, after taking the sample we are doing the calculations from which we will be able to find out the time durations for which V 0, V 1, V 2 and V 7 or any other sector will be used.

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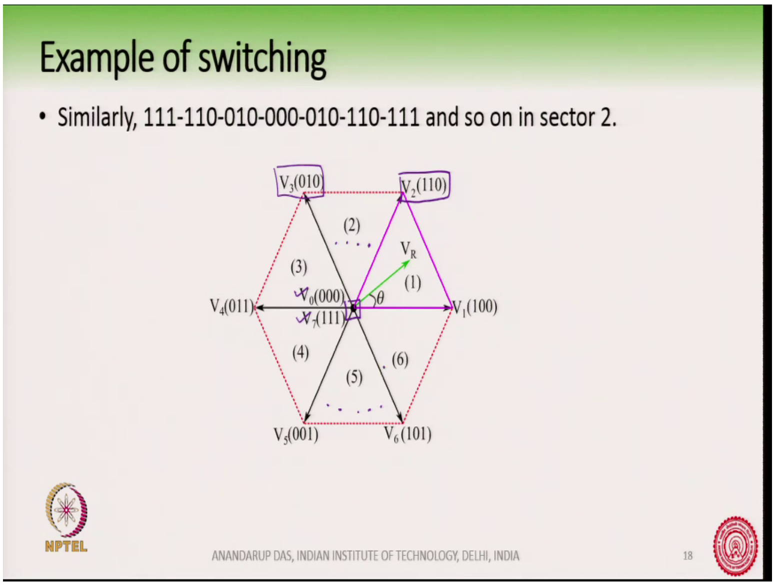

Similarly, it will be possible that for the second sector we will use this one, this one, this one and again this, so V 0, V 0. So, the switching will be 111, 110, 111 and then 110, 010 and 000; again, 000, 010, 110 and 111. So, this is how the switching in sector 2 will happen. And you can similarly find out the switching in when the reference vector is in this position then the switching is happening in sector 2. Similarly, you can find out for example, if the reference vector is in sector 5, then the switching how will the switching happen, which are the vectors involved and what are their timings.