High Power Multilevel Converters – Analysis, Design and Operational Issues
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Lecture - 29
Neutral Point Clamped Converter – Space Vector PWM

Now, we will see how we can switch the vectors in order to realize the reference vector.

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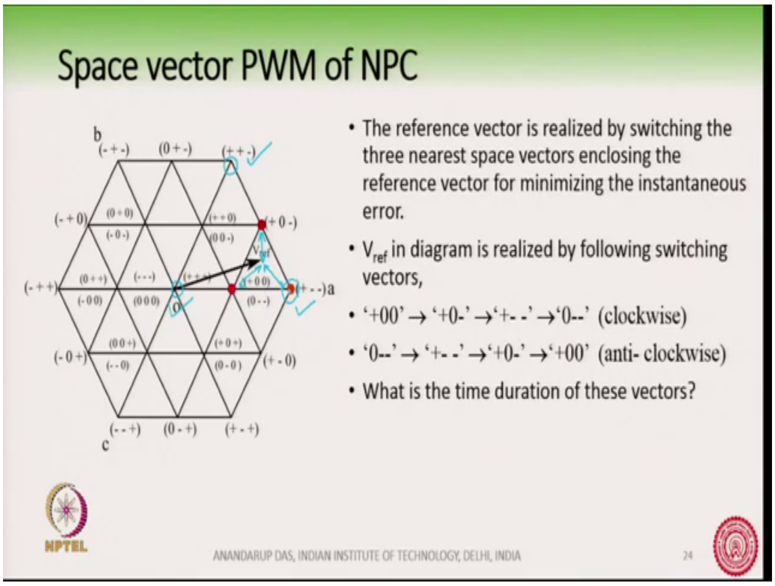

Again like the 2 level space vector diagram, the reference vector is realized by switching the three nearest space vectors enclosing the reference vector for minimizing the instantaneous error. So, suppose my reference vector is here, I will switch the three space vectors, which are nearest to this V ref and enclosing the tip of V ref.

So, of course, you why am I doing that why are we doing like this, because we want to minimize the instantaneous error, between the actual V ref and the between the V ref and the actual vectors which we are switching ok. Remember now that you can have a feel of the instantaneous error. See this is for example, V ref this is the vector V which we which we want to realize. Now we have these three vectors which we are actually switching from the converter.

So, therefore, we have this much of instantaneous error present ok, this much of instantaneous error is present between V ref and the actual vectors which we are switching right. And this instantaneous error is the source of harmonics right. So, we could as well we could have also switched this vector, this vector and this vector; we could have also done like that.

However, if we had chosen these three vectors, you can readily understand that the instantaneous error between V ref and the vectors, which we are switching this will be much more as compared to the case I have shown here.

So, the instantaneous error gets reduced, once we have chosen space vectors which are nearby and in fact, they are enclosing the reference vector ok. So, with that we are minimizing the instantaneous error right. And so you so, if suppose I did not have a three level space vector diagram, if I had a 2 level space vector diagram and I wanted to realize this V ref; I had no choice other than this one this one and this one ok, which would have caused instantaneous errors of magnitude this much, this much and this much ok. But now with a three level space vector diagram, I am switching nearby vectors which in through which the instantaneous error is reducing.

So, the harmonic profile will also get improved, the magnitude of the harmonics will go down automatically. And so, the three level space vector diagram is kind of like we have more densed space vectors present in the space vector diagram, which makes sure that the instantaneous error is going down. So, with more and more densed placement of the space vectors in the space vector diagram, the instantaneous error will go on reducing.

So, for example, this is a three level space vector diagram, if you have a five level space vector diagram, if you have a seven level space vector diagram; the whole diagram there will be many many more space vectors and they will come closer and closer to each other.

So, if you switch on those vectors for example, if you switch the three nearest vectors in a seven level space vector diagram, the instantaneous error will further reduce it will become very small. And so, the effect is that we will get a more and more sinusoidal voltage the voltage waveform will come closer to sinusoidal; that is what we are aiming with a multi level space vector diagram ok.

So, in this case suppose, we are suppose we are switching these three vectors, then how will we switch it? So, let me rub this thing off the instantaneous error let us rub this thing. And see that if the V ref is here and we are switching these three vectors ok. Then which are the switching states we are using. So, we go to the switching states for this vector which are plus 0 0 and 0 minus minus. And this vector has a switching state combination of plus minus minus this as plus 0 minus. So, therefore so, when we switch these vectors we go by this switching sequence either this one or this one. So, suppose we go from this plus 0 0 and then, we can go to plus 0 minus we can go to plus minus minus and 0 minus minus.

So, we like as if we are placing these vectors in a the placement of these vectors is kind of like clockwise placement of the vectors in switching. We can as well do an anticlockwise movement like 0 minus minus. From 0 minus minus, we can go to plus minus minus plus 0 minus and plus 0 0 ok. We could have also moved anti clockwise in the selection of the space vectors.

So, but you observe one interesting fact and that is that, when we move from one switching state to the other switching state only one phase is changing the there is switching only in the one phase. So, suppose you see plus 0 0 and plus 0 minus; only the c phase is changing from 0 to minus. And from here to here, you see plus 0 minus to plus minus minus. So, the b phase goes from 0 to minus and a and c remains the same.

So, when this switching transitions are happening only one phase is changing its state and that to from say 0 to minus or 0 to plus; never does it go from minus to plus or plus to minus. So, you will see here always the switching is happening in any one phase and it is going say plus to 0 or 0 to minus something like that. So, you can switch like this like we have also seen in 2 level space vector diagram; we can switch the three vectors.

So, the question then comes up is what are the timing duration of these vectors which again follows from the same principle of volt second balance which we had earlier also covered. So, we will utilize the same principle of volt second balance like in 2 level space vector diagram. And we will switch these three vectors for a certain duration of time. So, these duration of time is kind of like putting weights at the three corners of this triangle so, that the V ref can be moved on, the right side of the triangle or on the left side of the triangle.

So, this is kind of like putting three weights the duty ratio. Or the weightages are decided by the time for which these vectors will be switched.

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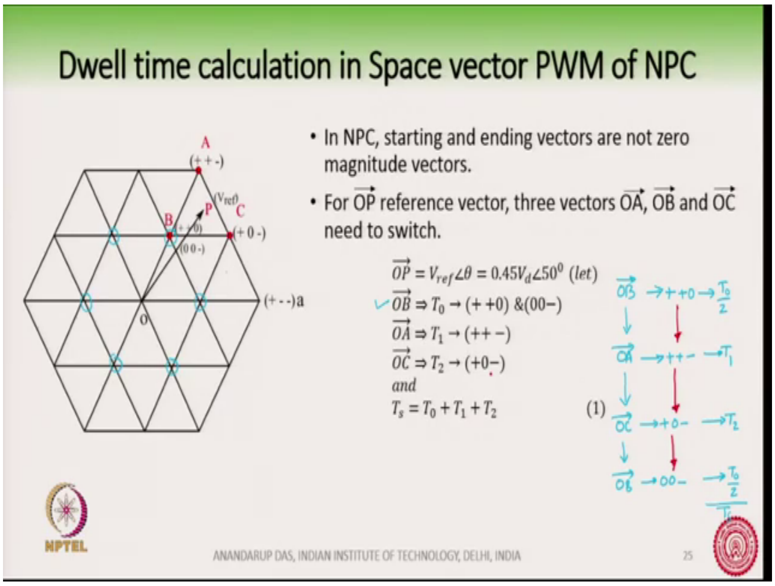

So, let us take an example ok, let us take an example. So, suppose we want to switch V ref which is at the point P. So, the three nearest vectors are ABC here ok. And let us take an example for OP reference vector, the three vectors OA OB OC need to switch fine.

So, OP vector we are just giving you an example. Suppose OP vector is given by V ref angle theta that is 0.45 V d at an angle 50 degree just an example. So, we will switch OB for T 0 time OA for T 1 time and OC for T 2 time. So, that T s the total switching time or total switching cycle is T s is equal to T 0 T 1 T 2 T 0 plus tone plus T 2.

So, that in a switching cycle, we will use the OB vector for T 0 time OA vector for T 1 time and OC vector for T 2 time. The question that may come up is why OB vector is kind of like the chosen vector for T 0? You could have also switched it for other durations like OC vector can be chosen for T 0 and OA vector can be chosen for T 2 time and something like that; it is also possible.

However, if we choose OB vector as the starting and ending vector then it will give us minimum switching ok. The switching transitions will be minimum; for that reason we always choose these vectors as the starting and ending vectors we always choose OB. So, these 6 vectors this vector, this vector, this vector, this, this and this; these six vectors are always chosen as the starting and ending vectors in a switching cycle T s. In order to minimize switching ok, that gives the minimum switching.

Now note that these starting and ending vectors, if you remember the 2 level space vector diagram; the starting and ending vectors where both of magnitude 0 vector. We had started from. If you remember the 2 level space vector diagram let me go back to that slide the start.

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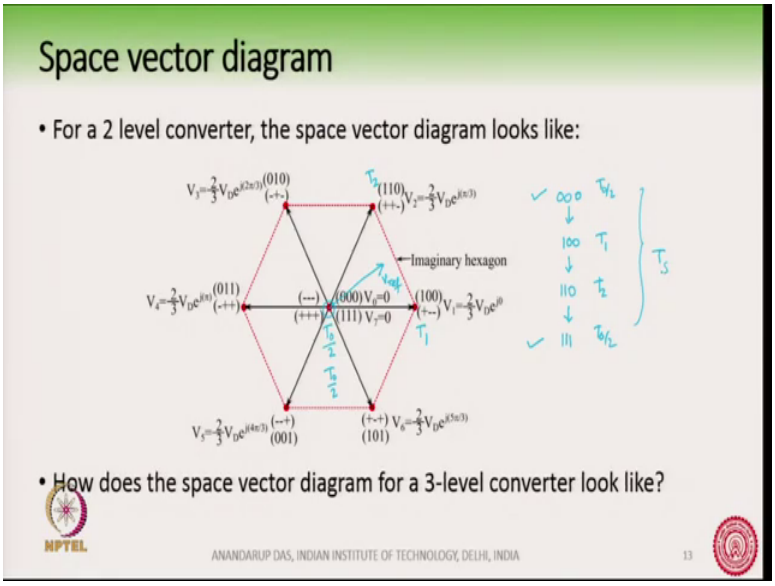

So, if there was a V ref something like here if there was a V ref we started with this vector. So, this vector was switched for example, T 0 by 2 period, then this vector would have been switched for T 1 period this for T 2 period and again T 0 by 2 period.

Something like, 000 going to 100 and going to 110 and again 111 ok; so, T 0 by 2 T 1 T 2 and T 0 by 2; now this is how it was switched remember that. So, in this 2 level space vector diagram the starting vector which is this one and the ending vector in a switching cycle. So, this is the switching cycle T s. So, the starting and the ending vector are of 0 vector, they were 0 vectors magnitudes 0 magnitude.

But in this case you see that, the starting vector and the ending vector which will be OB ok. This vector is the starting as well as the ending vector this vector will not have a 0 magnitude ok; it has a nonzero magnitude. And so, this OB vector for example, we will switch like OB for the switching combination say plus plus 0; for T 0 by 2. For example, this is 1 of the switching strategies. So, OB vector with a multiplicity of plus plus 0, we will switch for T 0 by 2 time period. And then we can switch OA vector for T 1 time period and the multiplicity will be plus plus minus ok.

And then we switch the OC vector, OC vector is plus 0 minus and we will switch for T 2 period. And then we will switch again OB vector, but now the other multiplicity of OB vector. So, the other multiplicity of OB vector will be 00 minus and then again we can switch it for T 0 by 2 period note that. So, this is how the whole switching cycle. So, this total is equal to T s right, this is how the total switching happens. So, note that here this transition from here to here has only one change of state of one phase.

So, plus plus 0 2 plus plus minus only c phase is changing from 0 to minus. So, there is only 1 switching transition similarly from here to here and similarly from here to here, there are only 1 switching transition happening. So, this is how the vectors will be switched and then we can find out what are the magnitudes of T 0, T 1, T 2 by again doing a volt second balance which we have shown here in this diagram.

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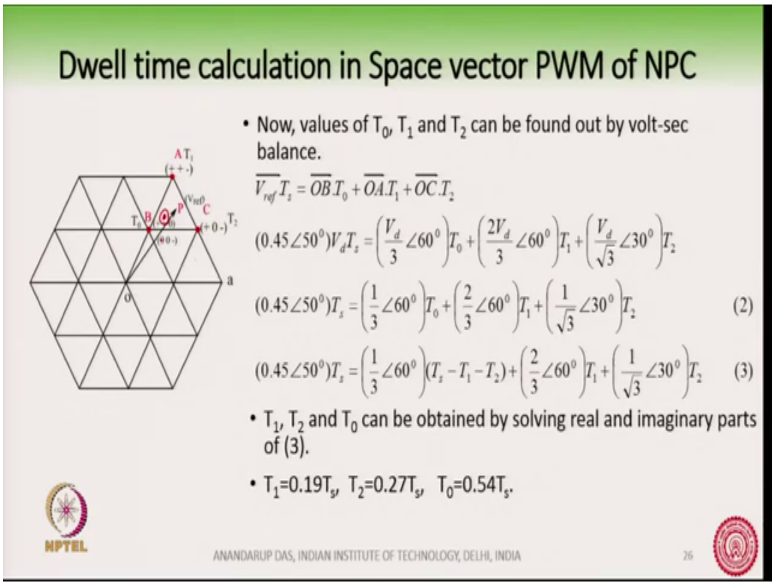

So, we can find out exactly for how much duration of time the vectors b. So, vectors at b c and a locations need to be switched on. So, for that T 0, T 1, T 2 can be found out by saying that V ref into T s time period is OB into T 0 plus OA into T 1 and OC into T 2 time periods. So, then V ref is 0.45 angle 50 degree times V d and OB OB is nothing, but V d by three angle 60 degree.

So, this is the vector OB and then you have OC sorry OA OA is two-third V d at an angle 60 degree and OC is V d by root three at an angle of 30 degree ok. So, once you put these values, then it is possible for you to find out T 1 T 2 and T 0 by solving the real and imaginary parts of equation 3. So, then you find that T 1 is equal to 0.19 T s, T 2 is 0.27 T s and T 0 is 0.54 T s. So, this shows that T 0 has the maximum weightage the T 0 time duration; that means, the vector OB has the maximum for a maximum time on a switching period T s OB vector has been switched on; see more than 50 percent of the total T s time period.

So, which means that, this vector should have been much closer here; so, it should have been like here. It is more close to the vector b vector at point b and T 1 is 0.19 and T 2 is 0.27. So, it means that so, there this is that their relative weightages. So, yeah so, that is what is shown here as T 0 is maximum OP vector is closer to OB.

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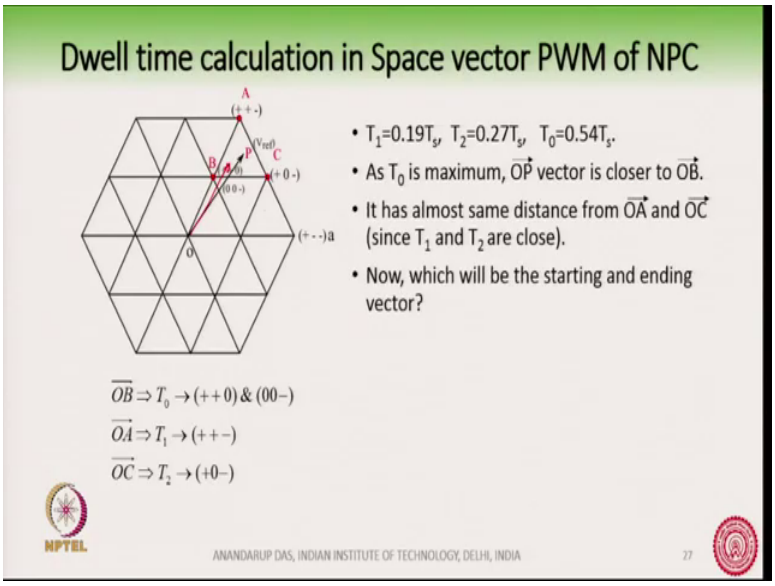

So, this diagram is like it should have been and more accurate diagram. If we had drawn it by scale should have been like something like this probably.

Now the now the question is as I was discussing, which will be the starting and ending vectors. So, now, we have known that these are the weightages of the three vectors and which 1 will be the starting and ending vector.

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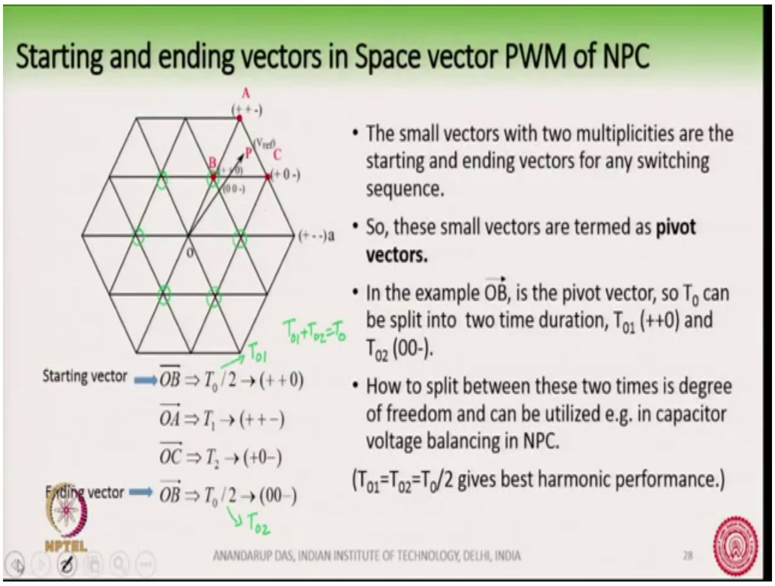

So, for that we find out for that we observed that the we should start with the b vector ok. We should start and end with the b vector as it is shown here. We start with the OB vector as I was also this is what I have already explained, but again after two slides, it is shown. So, we start with the OB vector and then go to OA OC and we take this this route of switching the vectors.

So, this is what is shown in this OB vector then OA then OC and again OB. So, this is the this vector is a starting then we go to here, this vector which switch for T 1 duration, then we switch this vector for T 2 duration and again the T 0 by 2 vector this one. So, these starting and ending vectors are always the small vectors ok. The starting and ending vectors will always be the small vectors. So, this means that either so, this or this or this or this or this or this will always be the start and the end vectors.

So, it will produce the minimum switching fine. So, these vectors are often called the pivot vectors pivot vectors means the switching sequence we will start from this vector and end in this vector. So, in this example the OB vector so, each is switched for T 0 by 2 and T 0 by 2. So, this is the this vector is the starting or the pivot vector.

Similarly you have 6 such pivot vectors present in the space vector diagram. Now here one thing that is that you may ask why did I choose the starting and ending vectors to be T 0 by 2 and T 0 by 2? Ok, that is a very natural question to ask why this T 0 by 20 0? I could have also taken any other ratio right, I could have taken say T 0 by 3 as the start vector, we will switch for T 0 by 3 duration and the end vector can be 2 2 by 3 times 2 is T 0 also right.

What we need is that the total T 0, because as per this equation. As per this equation here the total T 0 is what matters ok, the total T 0 for OB vector is what matters. Now what we are doing we are splitting this T 0 into 2 parts T 0 by 2 and T 0 by 2 and putting the vectors. You may ask that why T 0 by 2 and T 0 by 2? I could have also do it I could have done it with say T 0 by three two-third of T 0 starting.

So, this is actually so, in a general case we can say that this pivot vector can be split into 2 time duration T 0 1 and T 0 2. So, this is a more general form. So, it can be. So, instead of T 0 by 2 here we can say that OB vector can be switched for T 0 1 time and this ending vector can be switch for T 0 2 time ok; this is a more general expression instead of T 0 by 2 and T 0 by 2. So, this is a degree of freedom ok, we can choose we can choose any value of T 0 1 and T 0 2 as long as T 0 1 plus T 0 2 is equal to T 0.

So, this T 0 1 plus T 0 2 is equal to T 0. As long as this is satisfied then we are fine with it. Now so, later when we do the capacitor voltage balancing or the neutral point voltage balancing of NPC; we will utilize this degree of freedom. We will see that by manipulating T 0 this total 0 vector into T 0 1 and T 0 2 and making them unequal can help us balancing the midpoint voltage of NPC. This is a degree of freedom; however, for the best harmonic performance.

We will have T 0 1 equal to T 0 2 and is equal to T 0 by 2 it gives the best harmonic performance is more symmetric. But this T 0 can be split into this unequal T 0 1 and T 0 2, it is not only used for balancing the capacitor said there are many other types of PWM techniques. And you can see advanced literatures on that, in which this splitting of T 0 into T 0 1 and T 0 2 can have other consequences. For example, you may want to minimize the ripple the torque ripple on a motor.

Then you can make T 0 1 and T 0 2 unequal. There are also strategies to minimize losses in the neutral point clamp converter for which you may want to use a discontinuous PWM. In discontinuous PWM you may make T 0 1 equal to 0 and T 0 2 equal to T 0. So, 1 T 0 1 you have completely eliminated and the other the whole T 0 is given by T 0 2. So, these are advanced PWM techniques by which other functionalities. So, there are several functionalities which can be controlled by this degree of freedom.

So, one of them like is the midpoint balancing of the NPC, the other maybe like minimizing the torque ripple or the current ripple for a grid connected converter and torque ripple for an induction motor. You can also try to optimize the losses in the converter by this degree of freedom ok. However, T 0 1 equal to T 0 2 which is equal to T 0 divided by 2 that is 0.5 T 0; this gives you the best harmonic performance.

One interesting use of the pivot vectors is that the three level space vector diagram can be switched based on like very similar to a 2 level space vector diagram. That is one of the use of this pivot vectors and we will see it now. How can a three level space vector diagram can be looked as if it consists of multiple number of 2 level space vector diagrams. So, from the diagram itself from if you see this diagram here ok.

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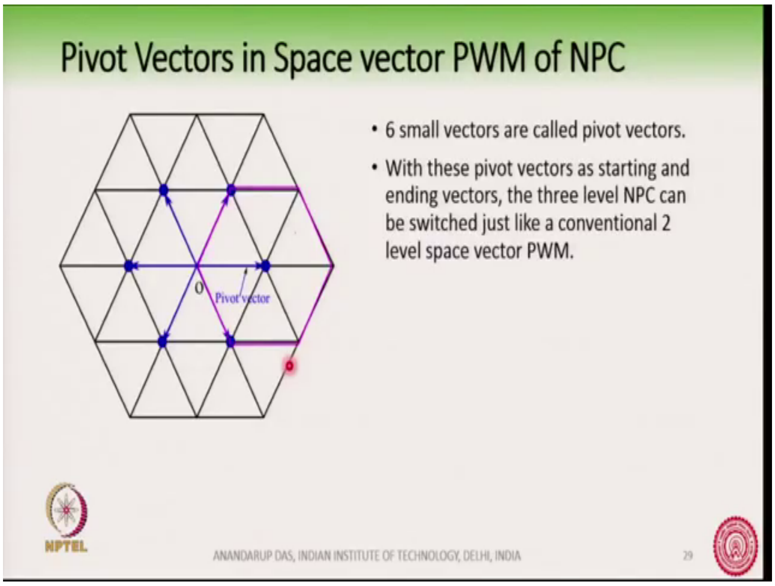

So, let us go to the next slide and see that this diagram the big hexagon here like you can see there are many many small hexagons here ok. So, this is the starting point like. So, this big hexagon of a three level space vector diagram is make is made up of many small hexagons ok. There are many small hexagons here smaller hexagons, how can I utilize the concept of 2 level space vector diagram into a three level space vector diagram.

So, in order to understand, we see that if we make the pivot vector as the starting and ending vectors in a switching cycle. Which we have just explained with taking this b point b as the pivot vector we had we had done a switching with a starting and ending with the b vector. Then the this portion of the space vector diagram can be thought of like a part of the 2 level space vector diagram. So, for example, I have shown pink colored hexagons here with the center of it as this pivot vector of a three level space vector diagram.

So, there are six pivot vectors of the three level space vector diagram out of which I have taken of this pivot as the pivot vector and I am drawing a hexagon over it ok. And this hexagon is kind of like representing the two level space vector diagram. So, with this six pivot vectors, we can actually split the hole the big hexagon into six small hexagon. So, this is what I have shown it here.

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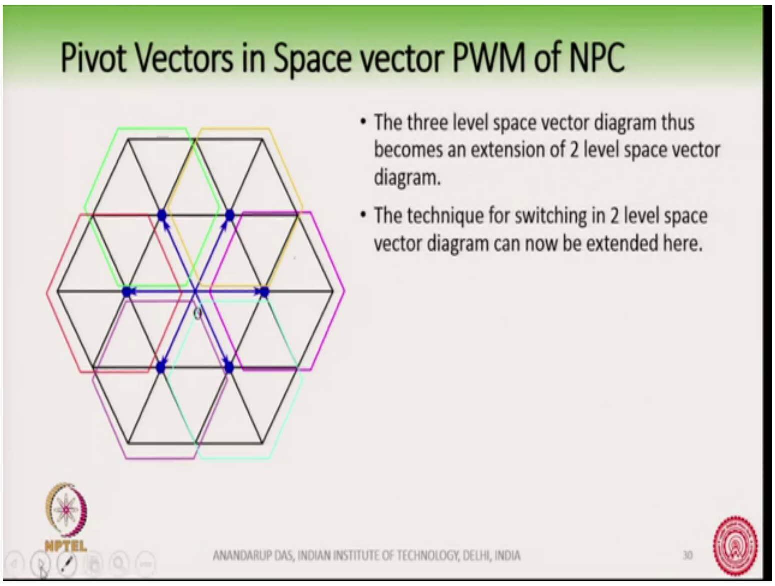

You see here that the; this is the big hexagon which is the black one here. But there are several colored hexagons. These smaller hexagons are corresponding to the two level space vector diagram.

So, you see this pink one has this as the pivot vector, the yellow one has this as the pivot vector; the green one has this as the pivot vector. The red one has this as the pivot vector, the violet one has this as the pivot vector and this light blue colored, this one has this as the pivot vector. So, with the pivot vectors as the center point of these hexagons, I can split the three level space vector diagram into six smaller 2 level space vector diagrams. What is the advantage of that? The advantage of that is that we will be switching just like a 2 level space vector diagram. So, we will not have to make a new strategy for switching a three level space vector diagram.

So, the 3 level space vector diagram switching therefore, becomes an extension of the technique for switching a 2 level space vector diagram. If we visualize the bigger hexagon as something like made up of 6 smaller hexagons like this; with the pivot vectors like this here. So, once we visualize the bigger hexagon like this it becomes easier for us to do the pulse width modulation on the three level space vector diagram. So, in order to go into this 1 we understand that with this as the pivot vector this hexagon can be switched just like a conventional 2 level space vector diagram.

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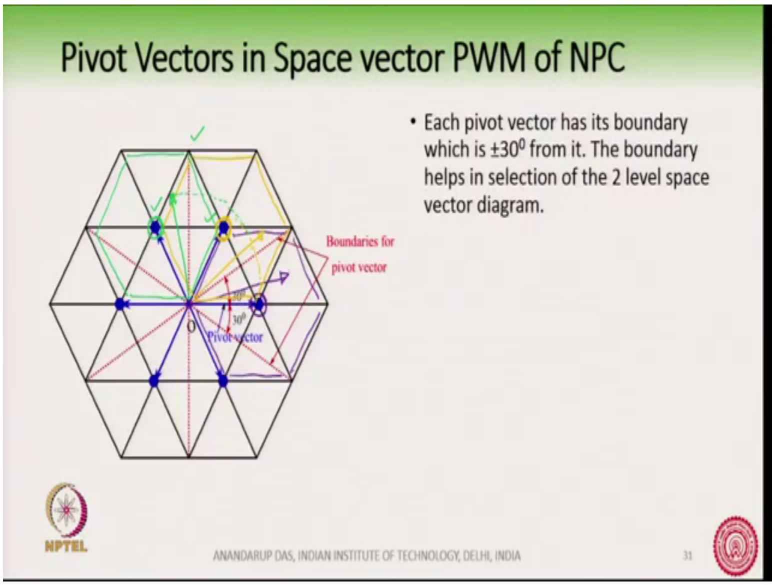

So, here so then of course, 1 question comes is where do you find that we will have to go from this pivot vector to this pivot vector or from this to this. So, this is shown by the boundaries here. So, I mean when the reference vector is here. So, this boundary shows something like let me take an example. So, if the reference vector is here ok. So, I will switch this hexagon here with the pivot vector here. So, this is the pivot vector and I will switch this hexagon which is given by this, this, this, this.

So, this will be a like a conventional 2 level space vector diagram. However, if the reference vector goes here the reference vector is rotating it is rotating like this. So, once the reference vector comes at this position which is shown by this yellow color line then what happens? Then, we have crossed the boundary of this pivot vector. So, actually now this becomes the pivot vector and this becomes the hexagon on which the switching should take place.

So, from the violet colored from the violet colored hexagon after crossing the boundary we have now moved into the yellow colored hexagon ok. So, this is the next 2 level space vector diagram which we will use with this as the pivot vector. So, this boundaries for pivot vector indicates these 30 degree lines which will say that from one hexagon from one 2 level hexagon how or when to move to the next 2 level space vector diagram.

So, this is how it will jump. So, once again so, if this yellow one goes to some other place so, this is rotating. So, this is rotating and rotating and coming like this. So, once it goes say here ok, once it goes to here then this will become the hexagon ok. With this as the pivot vector that is the starting and ending vector will be here. And for this position we will switch this one this one and this one; these three vectors we will switch because it is enclosed by this triangle here.

But the starting and ending vector that is the pivot vector this pivot vector will be the starting and ending vector for the reference vector at this position. So, this is how the switching action takes place for the in pc of course, we can do this by carrier based PWM we will do it by carrier based PWM. So, we do not have to kind of like all the time multiplying these and getting the mathematical expression that is not needed.

We can do with carrier based PWM, but this is how the actual switching takes place inside the space vector diagram. So, here also we if we go a little bit more in details of how the switching transition takes place and how the exact transitions take place.

So, suppose we have taken an example suppose the reference vector is rotating and we have taken four positions ABCD.

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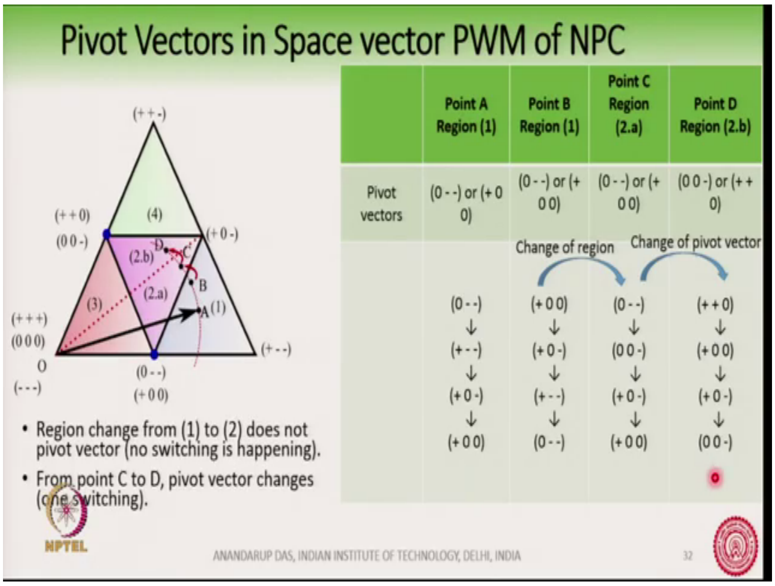

So, suppose we are at point A; so, if we are point A and we are in this position so, the pivot vector is this one. So, we start from this the switching. So, we start from 0 minus minus that is going from here 0 minus minus and then we go to plus minus minus. So, from here to go to plus minus minus, then go to plus 0 minus that is go to this plus 0 minus and then plus 0 0 this is how we can switch. These four vectors in order to realize the reference vector at point A ok.

So, this is the first one. now in the next sample this vector has moved to position B it has moved to B. So, what we will do at B we can switch this plus 00 to plus 0 minus plus minus minus and 0 minus minus. So, we first made an anticlockwise movement and then at point B we had made a clockwise movement. Other types of PWM note that other types of PWMs are also possible symmetric a symmetric PWM, but we will we are taking a simple example here ok.

So, during this entire switching you should note that from here, there is one switching transition another switching transition. And another switching transition, but when we switch from A to B there is no transition here ok. There is no transition and then the switching happens with one transition here one transition here and again coming back to 0 minus minus. Now we are for example, taking going to point C ok, now we have crossed one triangle. So, earlier A and B where within this triangle now we are moving to this triangle having the same pivot vector.

So, we move from point B to point C in the next sample. So, at point C we see that our pivot vector is again this one. So, we will start and end at here, but now we have to switch these three vectors. So, how we will do it? So, we have come here at 0 minus minus. So, from 0 minus minus, we will go to 00 minus then plus 0 minus and plus 00. So, we are going from 00 minus, we go we are going to 00 minus here and then plus 0 minus and coming 2 plus 00.

So, here also there is no transition, but there is one switching transition everywhere from here to here from here to here and from here to here one transitions. Now suppose in the next sample let us take an example we are going from point C to point D; now this crosses the boundary of the pivot vector. So, as we move from point C to point D, then the pivot vector is changing. Now when the pivot vector is changing; that means, from this vector I have to now move to this vector and we have to start the switching sequence from this vector.

So, therefore, when it moves to D, so, from this plus 00 we ended here see plus 00 we ended here from here we will jump to here plus plus 0 ok; we will jump to here and then from here we will do the switching. So, from plus plus 0 then we go to plus 00; so, from plus plus 0, we go to plus 00 then we go to plus 0 minus and 00 minus. So, in this way we see that there is 1 switching happening in each of these transitions.

But, there is 1 extra switching when we are changing the pivot vector. For example, here we have changed the pivot vector. So, from this position to this position, we are from this multiplicity to this one, we have one extra switching happening because we are now shifting our pivot vector. So, as we move from point A to point B to point C in different regions. So, we have defined this as region 1 A and B are in region 1 and B and C and D are in region 2 A and 2 B ok. 2 A means part of this triangle, but inside under the control of this pivot vector and 2 B is this region of the triangle but switched with this pivot vector ok.

So, as I move from these regions the switching happens like this way ok. So, this gives you an example of how are we switching and we see that, when we have a change of the pivot vector we have one switching extra that takes place in this. Now this is only one way of switching I must admit here that this is one way of switching that we have explained here, there can be infinitely possibilities of switching.

And extensive work has been done and many papers have been published on different types of switching on NPC. Again as I told you they may be having different types of optimizations like capacitor in midpoint balancing and then switching loss reduction and torque ripple minimization like that.

So, this is only one basic type of switching, but many advanced PWMs with very elaborate switching sequences have also been proposed based on what is the requirement from the converter ok. So, with this we will see we have given a basic understanding of the PWM and we have to then go to the carrier based implementation of this.