High Power Multilevel Converters – Analysis, Design and Operational Issues
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Lecture – 28
Neutral Point Clamped Converter- Space Vector Diagram

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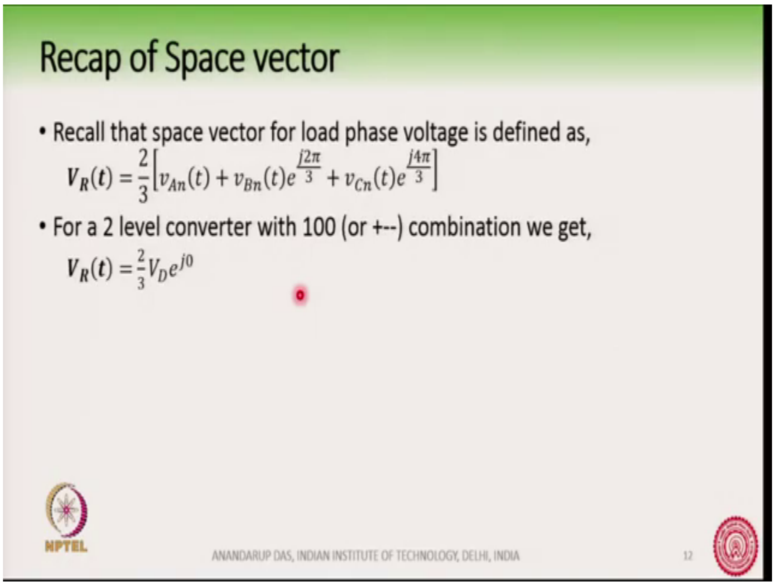

Hello. So, we continue with the lectures on Neutral Point Clamped Converter. In today's lecture, we will mostly focus on the space vector diagram of a 3-level neutral point clamp converter. So, before we go into the space vector diagram of 3-level neutral point clamp converter, let us first recall what is a space vector ok? Which we have covered earlier while discussing about the conventional two-level voltage source converter.

So, we had defined the space vector space vectors as a combination of 3 quantities. For example, if these 3 quantities are load phase voltages then, the resultant space vector is something written like this here ok. So, this is the resultant load phase voltage space vector.

So, you can have space vectors of different types of quantities: you can have space vector of current, you can have space vector of load phase voltage, you can have space vector of pole voltages of an inverter like that. And these quantities v An v Bn and v Cn which are instantaneous time quantities, they may be balanced or unbalanced.

So space vector is basically, a mathematical concept. Now, for a two-level converter we had earlier seen, so you can recap that with a 100 combination or plus 1 minus minus combination; that means, A-phase is connected to the positive DC-bus and B and C-phases are connected to the negative of the DC-bus.

So, that combination is called a 100 combination or plus minus minus combination. We have got the space vector of the load phase voltage as equal to two-third V D e to the power j 0 that is at an angle of 0 degree.

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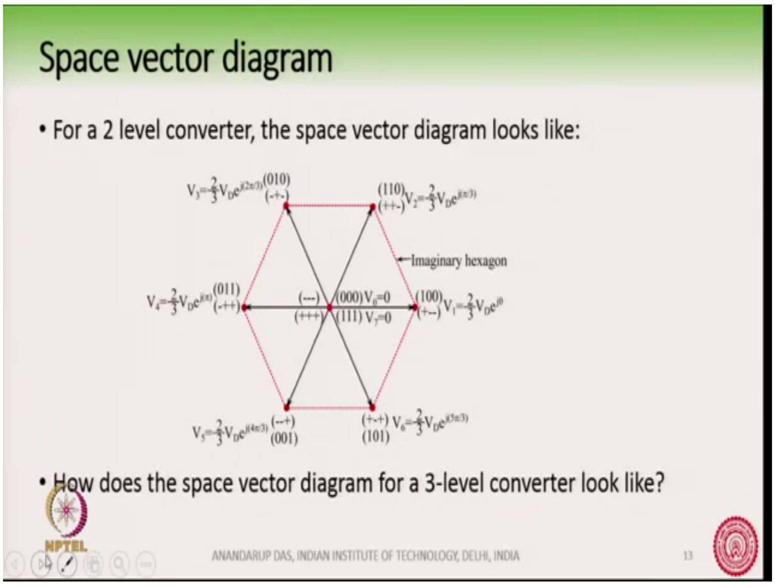

So with that, we had formed the space vector diagram which is now shown here. You can see here that there are total 8 space vectors, there are two 0 vectors here, which are corresponding to plus plus plus or minus minus minus combination. Whereas, there are 6 active vectors like this, which are having a switching state combination of something like plus minus minus plus plus minus and so forth. These, the boundary of this space vector diagram is an imaginary hexagon, ok.

So, this we know already. Now, next is how does the space vector diagram for a 3-level converter look like? So once we have understood 2-level space vector diagram, we can build up on that knowledge and can easily make a 3-level space vector diagram.

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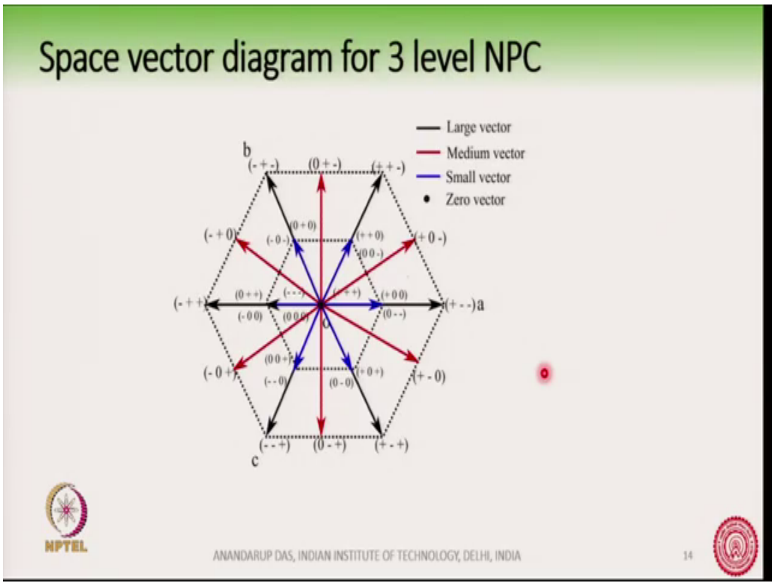

So let me first show you how does this space vector diagram look like? So, it is shown here, you can see there are many more vectors, how we derive this space vector diagram is what we will study today. So, there are many more space vectors. So, there is an inner hexagon and there is also an outer hexagon.

So, there is an inner hexagon something like this here, and there is an outer hexagon which is shown like this here and there are several vectors. So, these vectors some are marked with blue, some vectors are marked with red and some vectors are marked with black, ok. So, we will see how we get to these vectors.

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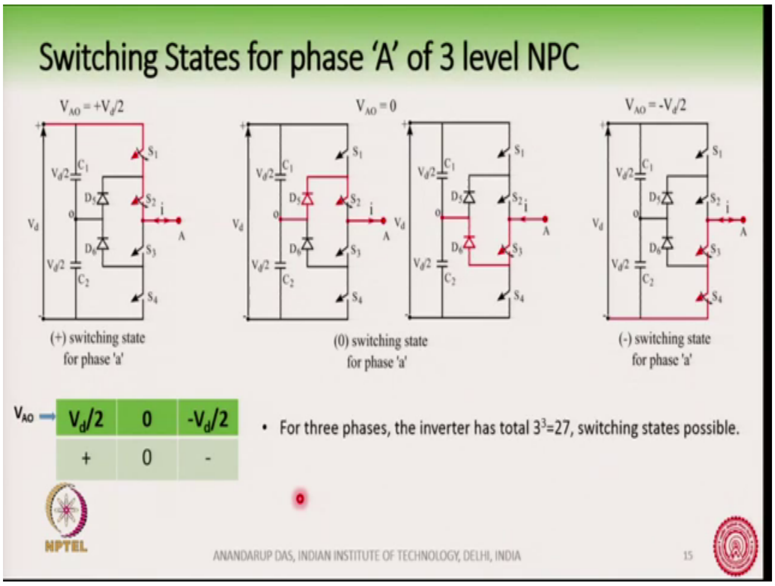

So, first we will see that in case of a 3-level neutral point clamped converter, the pole voltage has 3 switching states or 3 possibilities of the voltage not 3 switching states the pole voltage has 3 possible levels of output voltage. So, it can be V d by 2, it can be 0 or minus V d by 2. These are the 3 possible voltage levels that is at the point A with respect to the point o, so here.

And these 3 switching or these 3 voltage levels are denoted by plus 0 and minus, in the subsequent discussion. So, and here we have already covered it, but these are the directions of current which are flowing when these different types of switching states are used, right.

Now, so this means that in phase A we have 3 levels of voltages possible. Now, since there are 3 independent legs of this converter, so the total number of switching states possible can be 3 into 3 into 3. Because, there are 3 phases and each phase can have 3 possibilities. So, there can be total 3 into 3 into 3 or 3 to the power 3, that is 27 switching states are possible from this converter, ok.

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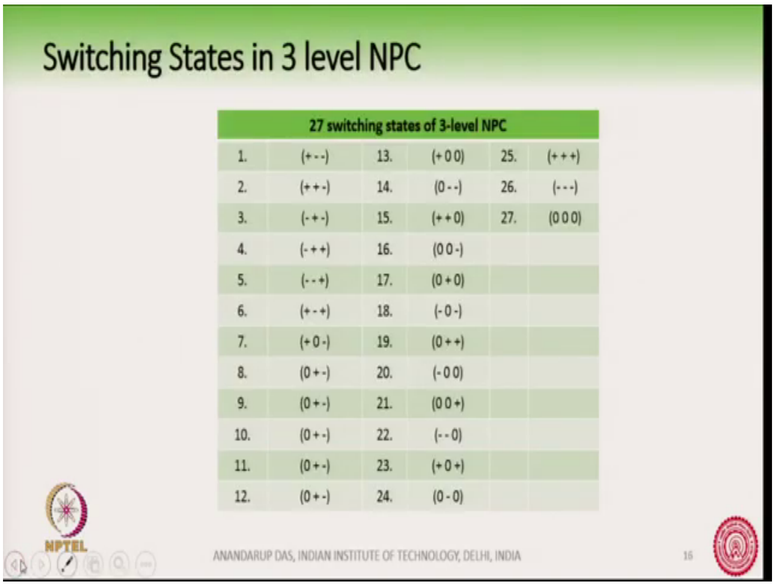

So, these 27 switching states of the 3-level NPC is shown here. So, you can see that for example, plus minus minus is one switching state, ok.

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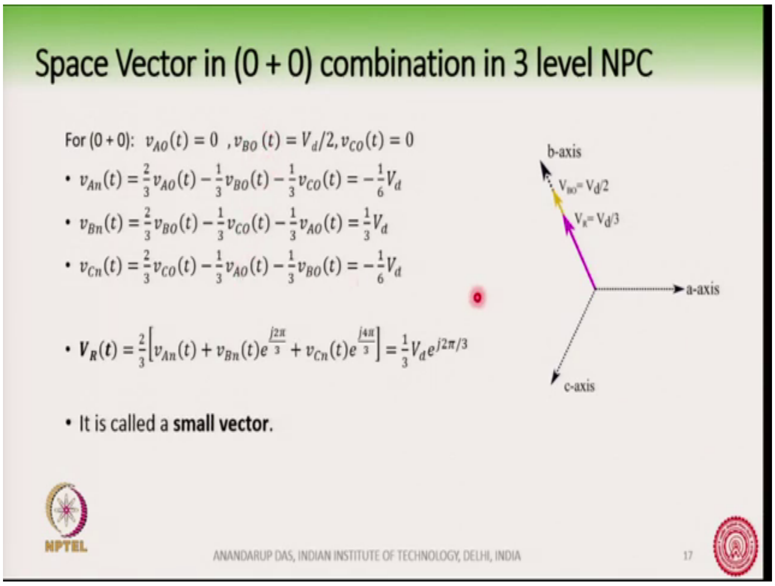

So, plus means the A phase is at V d by 2 and minus means the if B-phase is at minus V d by 2 and minus again means another minus means C-phase is at minus V d by 2. So, you can have 3 possibilities here, plus minus or 0, ok. On the A-phase, plus minus and 0. Similarly, you can have plus minus and 0 on the B-phase and plus minus 0 on the C-phase thereby, you have 3 into 3 into 3 that is, 27 possibilities. And which are listed in the table.

So, corresponding to this switching state, we can now draw the space vector diagram, ok. So suppose, we are drawing the load phase voltage space vector diagram ok. So, suppose we have we take one of the switching states 0 plus 0 ok. 0 plus 0 must be see for example, this 17 th number 17 0 plus 0 is one of the possibilities one of the switching states of the converter. So, this 0 plus 0 which means, that v AO the pole voltage is 0, v BO is v D by 2 and v CO is 0.

So therefore, we can write down what is v An t? v An t is two-third v AO minus one-third v BO minus one-third v CO. This we have seen while we were discussing the conventional 2-level converter, we had derived this part.

So, v An t is minus one-sixth V d v Bn t. Similarly, if you put these values here, will be equal to one-third V d and v Cn t will be again equal to minus one-sixth V d, ok. If you substitute these values here in the equation. So, this means that the V R t or the resultant space vector is given by this one and it you find it to be one-third V d and e to the power j 2 pi by 3. So, the resultant space vector has a magnitude of one-third V d.

So here, you can see how the space vector looks like. So, so the resultant space vector is given by this pink arrow, ok. And it has a magnitude of one-third V d ok. So, this is for one phase vector. In a similar way, you can draw space vectors for all the other 27 combinations, right. One by one inserting the values of v AO t, v BO t and V CO t and in a same fashion, you can go on deriving the resultant space vectors, ok.

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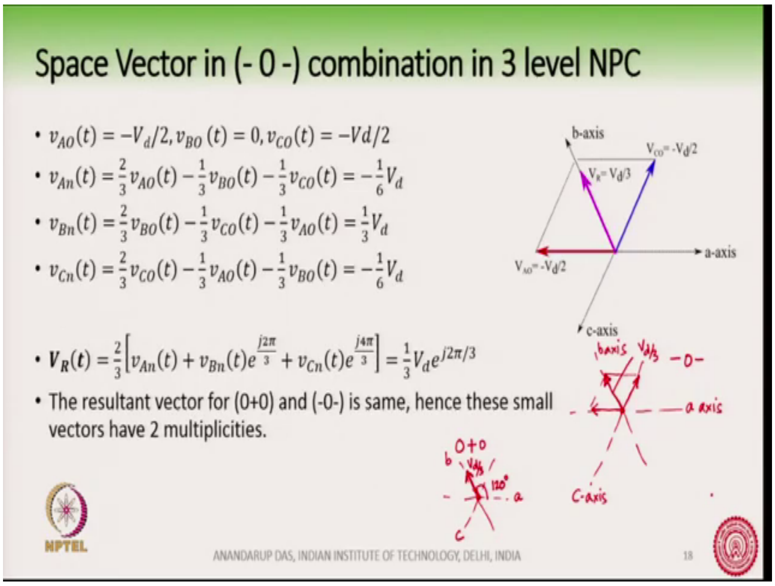

So for example, there is also one more example we have given here. So, suppose v AO t is for example, this is minus 0 minus combination, ok. Minus 0 minus combination, so, you put v AO t minus V d by 2 v BO t 0 and v CO t also minus V d by 2 and then you can find out v An t again like this. And then V R t are the resultant space vector as one-third V d e to the power j 2 pi by 3.

So, this vector was at an angle of 120 degrees e to the j 2 pi by 3, the angle was 120 degrees. And here also the one-third V d e to the power j 2 pi by 3. So, its the same vector. So, you see that these 2 combinations the 0 plus 0 as well as the other switching combination minus 0 minus. These 2 are producing the same vector, ok. The resultant vector for 0 plus 0 and minus 0 minus is same ok.

So, this tells us that both these switching combinations produce the same resultant space vector. And so, we say that this particular vector that is one-third V d e to the power j 2 pi by 3, this particular vector is having 2 switching state multiplicities or 2 multiplicities.

Because 2 switching state combinations produce the same vector. This is something which was not present in a two-level space vector diagram. It was in fact present, but like only for the 0 vector. For the 0 vector, if you remember the 0 vector had 2 multiplicities plus plus plus or minus minus minus ok. But all the other 6 active vectors in a two-level space vector diagram, they were having a single multiplicity.

In case of a three-level space vector diagram, we see that this particular active vector one-third V d e to the power j 2 pi by 3. This has in fact, 2 multiplicities, right. So, this is how the resultant space vector looks like. You do not always have to go through this mathematics to find out how the resultant space vector always looks. You can quickly also, diagrammatically come to the same conclusion.

For example, let me take this minus 0 minus combination. So, I can quickly draw. So, this is the a-axis, this is the b-axis and this is the c-axis for example. So, I can quickly find out the resultant space vector by factorial addition on a diagram, ok, without going into the detailed mathematics.

Say for example, you have minus 0 minus so, which means that on the a-axis, you have a vector which is minus this way. And on the b-axis you have 0, nothing. And on the c-axis you have another minus. So, on the c-axis you have another minus like this, ok. So, there is a minus V d by 0 and minus V d by 2 and so, the resultant of these 2 by the use of parallelogram law we can find that the resultant is like this, ok.

With the magnitude of because we have multiplied the 2 by 3 here so, the magnitude comes out to be V d by 3, ok. So, without even going through the detailed mathematics like this, diagrammatically the resultant can be easily obtained. You can also do the same thing for the previous combination that was 0 plus 0. So, this was for the minus 0 minus combination. So, how will it look like for the 0 plus 0? 0 plus 0 means on the a-phase.

So, again I draw the a, b and c phases. On the A-phase there is no there is no contribution. On the b-phase there is a there is a plus V d by 2 combination and on the c-phase, there is no combination.

So, A-phase this is the b-axis and this is the c-axis. So, on the a-axis there is no contribution, on the b-axis there is plus V d by 2 and on the c-axis there is no contribution. So, this resultant, so, this is plus means V d by 2. But again, we are multiplying by 2 by 3 here. So, this resultant is V d by 3 which we can directly write without going to the detailed mathematics, ok.

And we can immediately see that this angle will be 120 degrees. Fine, so a this is how we get to all the combinations.

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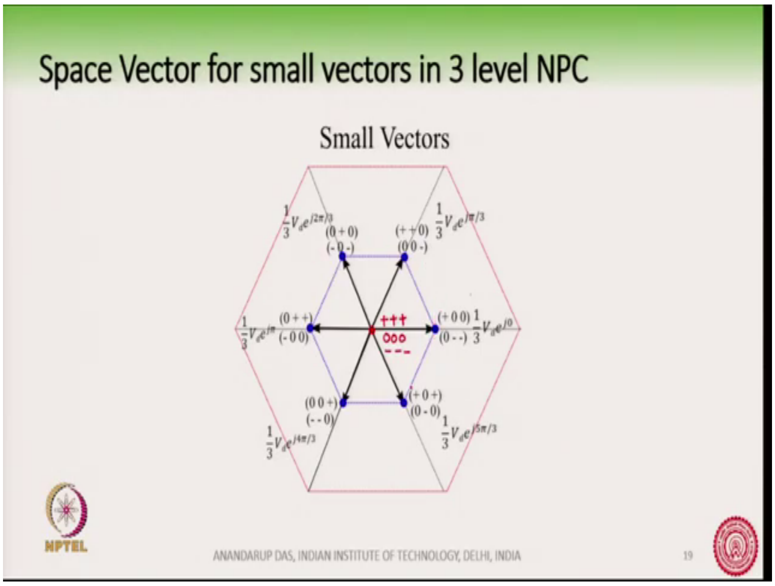

So, let us see that with these combinations how we get the vectors? So, these 6, so, there are the overall space vector diagram has 2 hexagons, the inner hexagon can be obtained by these switching state combinations which have been shown in the diagram, ok. So, if you take these combinations here, then you will always get to these 6 vectors on the inner hexagon, ok.

Of course, you have here 0 so 0 means what will be the 0 here? 0 means this will be plus plus plus 0 0 0 or minus minus minus. So, these vectors are here, ok. These are the smallest 3 0 vectors and then you have the 3 small vectors, there are 6 small vectors here, ok.

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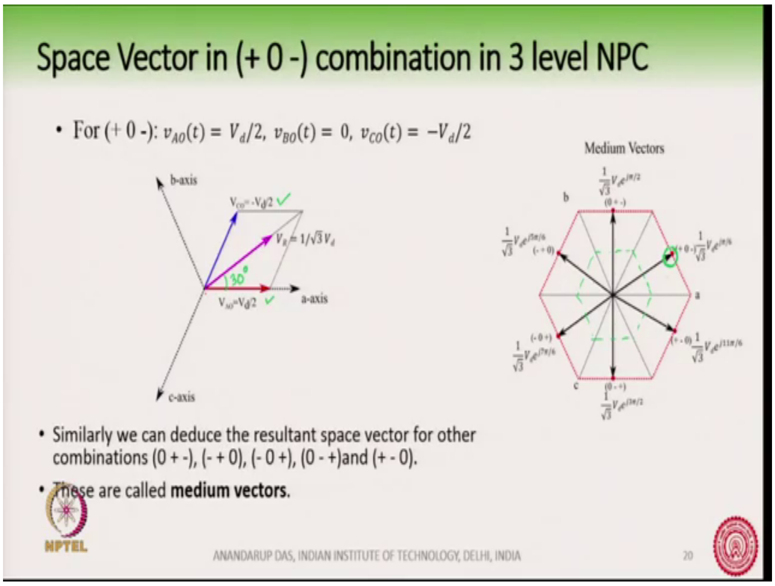

Now, let us take some other combination by which we will see that we will be able to reach the outer hexagon, ok. So, let us take a combination say plus 0 minus ok. So, if I take a plus 0 minus combination, I can then draw the resultant, ok. So, plus 0 minus means, on the a-axis, so let me take a different colored ink. So, on the a-axis, this V d by 2 because it is plus on the a-axis. So, v A 2 is V d by 2. So, this is V d by 2 here.

And then, on the b-axis it should be 0. The b-axis so, there is no nothing on the b-axis 0 and on the c-axis you have minus V d by 2. So, on the c-axis we have a minus V d by 2, whose position will be here, ok, minus V d by 2. So, this is the so plus 0 minus. So, the resultant of these 3, when we multiply by 2 by 3, we see that the resultant is 1 by root 3 V d, but at an angle of 30 degree here, ok.

So, the resultant of such a switching state combination, the resultant space vector for such a switching state combination will be on the outer hexagon ok. So, the inner hexagon is somewhere here, not shown. So, I will just draw a dotted line here the. So, the inner hexagon is somewhere here: half the size of the outer hexagon, ok. So, the inner hexagon is here. But the inner hexagon is what we have already covered. This is the inner hexagon.

Now we go so, with this switching state combination of plus 0 minus, the resultant vector is here. The resultant vector is here, ok. Plus 0 minus which is V d by root 3 at an angle of e to the power j pi by 6, ok, at an angle of 30 degree. So, these vectors are called medium vectors, ok.

These the vectors which we had obtained in this slide ok, these vectors are called small vectors because their magnitude is equal to one-third V d ok. However, for the medium vectors we see the so, the magnitude is V d by root 3 that is almost like 0.577 V d. So, it has a magnitude more than the small vectors and therefore, these are called medium vectors, ok.

There are 6 switching state combinations that produce this medium vectors and these switching state combinations are given here, ok. Say like plus 0 minus and then these switching state combination will give you the medium vectors. So, medium vectors are made with one phase as plus, one phase as minus and the other phase as 0 ok. So, these will make the medium vectors as shown in the diagram. Now, there is also there are some vectors which are even larger in size.

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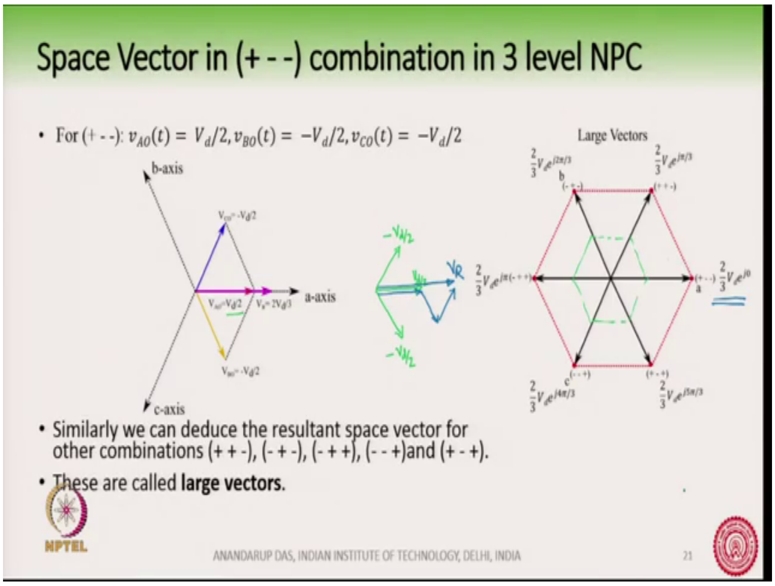

So, again I will so, this is shown in this space vector diagram, this will form the boundary of the space vector diagram. So again, I will use the dotted line to show you the inner hexagon, here and you have the outer, the vertices of this hexagon these are called the large vectors. And these are typically these are typically formed with switching state combination with like 1 vector as plus or 1 or 2 vectors as plus and the other vector as minus like that, ok.

So, we can take an example for example. So, we can take that plus minus minus. So, if it is plus minus minus. So, on the a-phase, the contribution from the pole voltage is plus. So, this means plus V d by 2 here. So, a-phase there is a plus here, a-phase is plus here and on the b-phase, you have a minus contribution. So, you have a minus contribution on the b-phase. And, on the c-phase you have again a minus V d by 2 contribution.

So, this is minus V d by 2. So, this is plus V d by 2, this is minus V d by 2 and this is minus V d by 2. So, if you add these 3, so I can add these 3 and can write like this here this and then this and then this ok. So, this will give me the resultant. This is the resultant V R. Again, with a two-third multiplying factor; and that, will when you do the multiplication, the magnitude of V R is two-third V d, ok.

Two-third V d of course, at 0 degree, 60 degree, 120 degree, 180 degree, 240 degree and 300 degrees, ok. So, these are called the large vectors, and these vectors have the these vectors form the boundary of the hex a boundary of the outer hexagon, ok.

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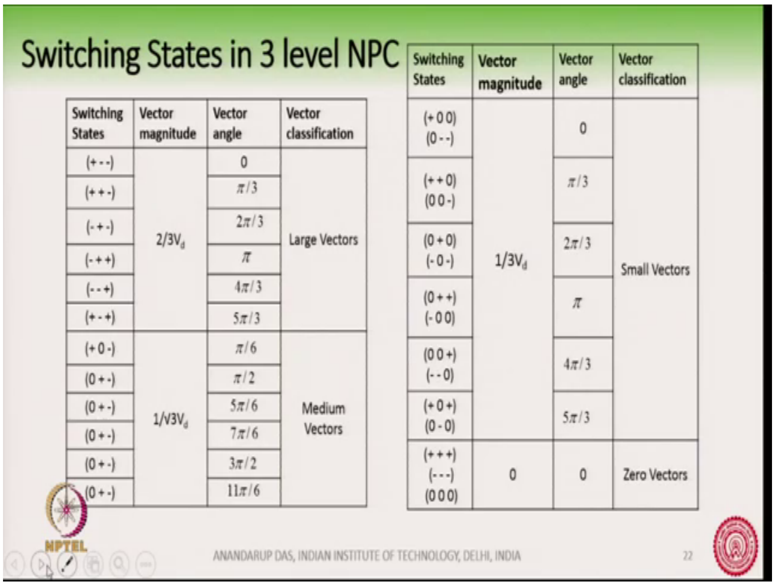

So this table here shows the different so, this table is kind of like a summary of what we were talking about. So, you can see here that the large vectors have a magnitude of two-third V d and they are placed at 60 degree intervals and these are the switching state combination for producing this vector, ok. Like this, these are the 60 degree angles are present here, 60 degree angles present here and having a vector magnitude of two-third V d.

Next, we have the medium vectors; so, there are 6 large vectors. Again similarly, we have 6 medium vectors. So, and their magnitude is 1 by root 3 V d that is 0.577, this is two-third V d means 0.66 V d, this is 0.577 V d and they are also displaced by 60 degree; however, from the large vectors they are displaced by 30 degrees. So, these are on the sides of the these vectors sit on the side of the outer hexagon.

Then we have 6 small vectors and these 6 small vectors are having magnitude of one-third V d and these 6 angles here. But each of these small vectors each of these small vectors have 2 switching state multiplicity. So, 2 switching state produces the same vector and these are listed here. And of course, we have the smallest vector that is the 0 vector and 3 multiplicities which are producing this here.

So, we see that we have 6 plus 6 large vectors 6 medium vectors and 12 so, if you see here 6 switching states produce large vectors, 6 switching states produce medium vectors, 12 switching states produce small vectors and 3 switching states produce 0 vector. So, 6 plus 6 plus 12 plus 3 makes 27. So, there are 27 switching states. So, 12 makes small vectors, 3 makes 0 vectors and 6 and 6 makes large vectors and medium vectors.

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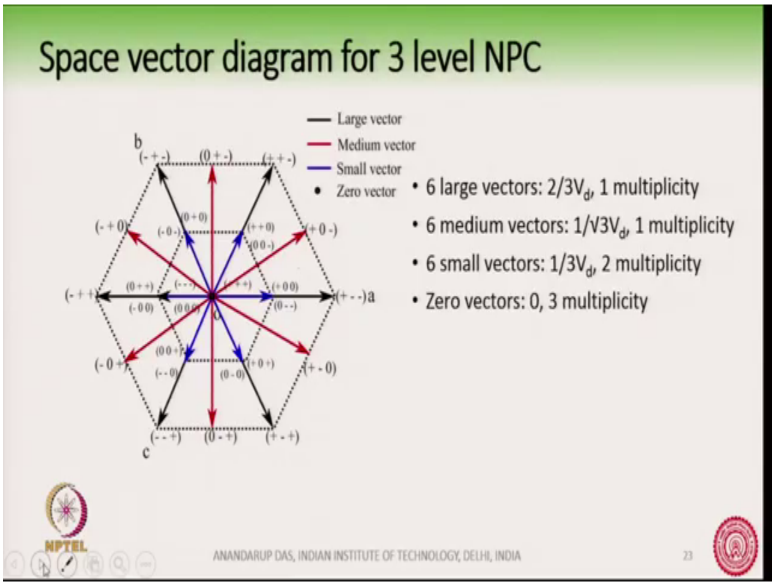

So, that forms the whole space vector diagram which is now shown in this figure, ok. So, these this is the whole space vector diagram. Again, sometimes so, these vectors are shown by these arrows. So, there are 6 here and there are like 12 large vectors sorry 6 large vectors and 6 medium vectors. So, the small vectors are given are indicated by the blue arrows while the medium vector is indicated by the red arrow and the black one indicates the large vector.

In many cases, in the book or something, or in the book or in the literature you will find that these vectors are often joined by lines.

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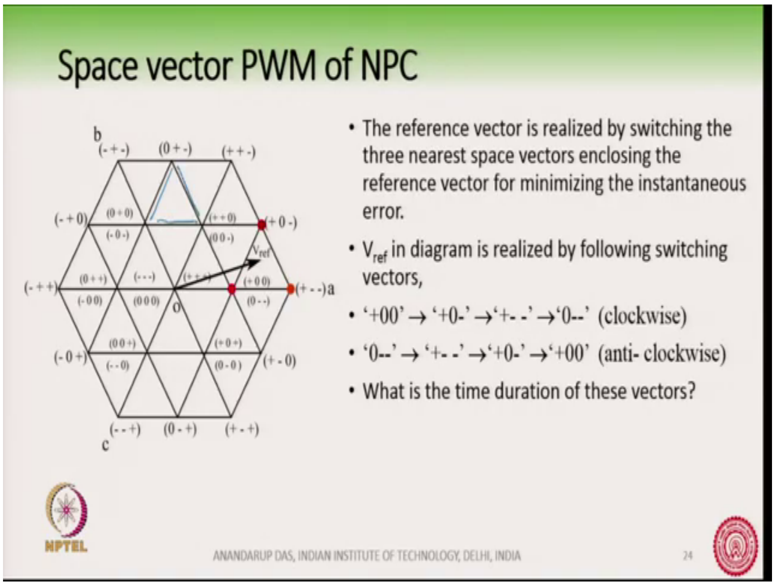

So yeah, so these vectors are often joined by lines that you will see in the book and you will see that such a space vector diagram is often shown, ok. But remember these lines here these intermediate lines, these are all imaginary, ok. What exists in the space vector diagram are just vectors at these points, ok. Vectors at this location, that is it. We just have these vectors at the location these intermediate line for example, this line or this line or this line these lines are imaginary lines.