High Power Multilevel Converters - Analysis, Design and Operational Issues
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Lecture - 33
Neutral Point Clamped Converter - Another Strategy of Capacitor Voltage Balancing

Now, we see one interesting technique for balancing the midpoint voltage with the help of virtual space vector. Now what is a virtual space vector? Virtual space vector is a space vector which is formed by using the normal space vectors ok.

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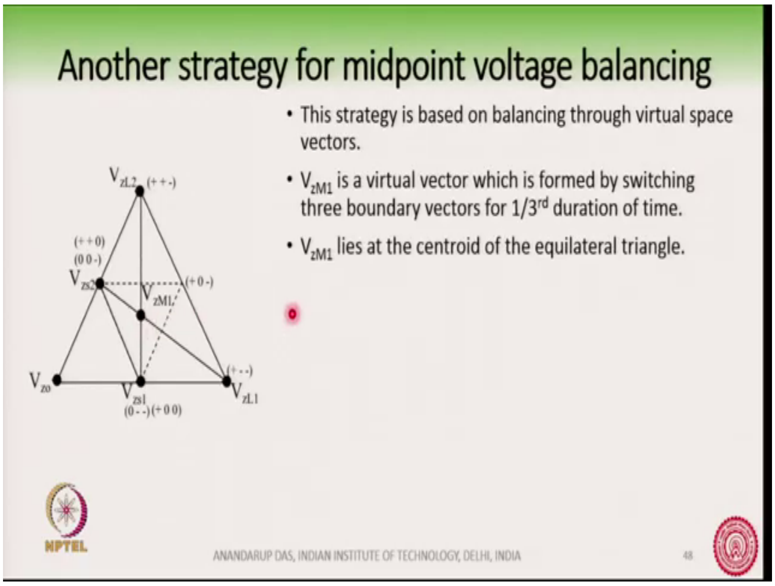

But for different durations of time for example, this vector one example say of a virtual space vector is V zM 1 ok. So, this is the vector here. This vector does not exist because, we do not have any switching state which will produce this vector. Of course, we have switching states that produce this vector, this vector, this vector, this vector, this vector and this vector. So, these 1, 2, 3, 4, 5, 6, these 6 vectors we can produce because we have switching states for them.

However this vector cannot be produced directly like the switching state. So, this vector, how can we produce? We can produce this vector by applying this vector, this vector and this vector for equal duration of time ok. If I apply this, this and this; these 3 vectors for equal duration of time, I will get to this vector which is at the centroid of the triangle ok. Similarly, if I apply this, this and this for equal duration of time, I will get this vector.

So, therefore, this V zM 1 which is shown here is a virtual vector which is formed by switching 3 boundary vectors this one, this one and this one. These 3 vectors can be switched for equal duration of time. So, as to produce this virtual vector V zM 1 which lies at the centroid of the equilateral triangle. Utilizing this V zM 1, we will be making the midpoint voltage fluctuations minimum. Let us see how it works.

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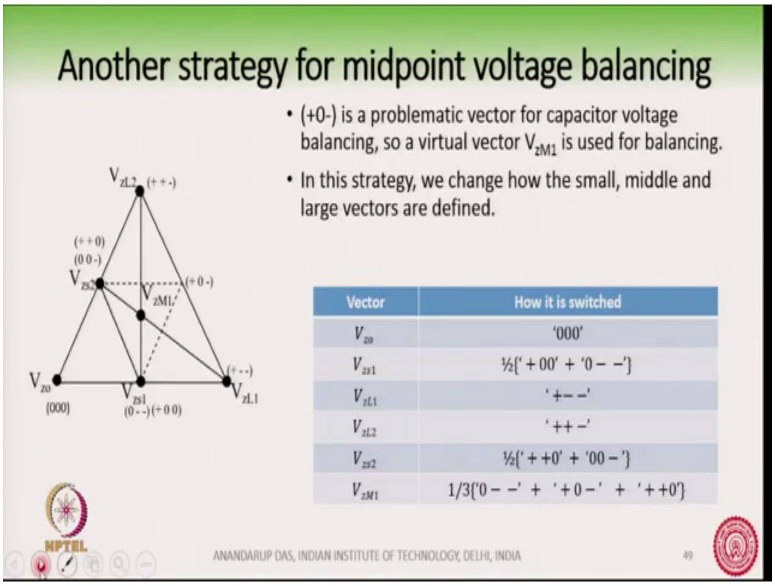

So, remember that we had said that plus 0 minus or the medium vector or the middle vector was the problematic vector ok, for the capacitor voltage balancing. So, this vector plus 0 minus, this vector will not be directly used ok. And we will redefine how we define the vectors in the sector. So, that is why you see here we have not so, we have used these black circles for the vectors, but we have not used any black circle here.

So; that means, this vector we will not use in the conventional way. We will redefine how the vectors are. So, how do we redefine the new vectors in this sector ok. So, far so, we are now redefining how the vectors are. So, this redefinition of vector is given as like this. So, let us see what are these vector V z 0 is this vector which is switched with 0 0 0 combination ok, plain and simple ok.

We are not going to use. So, in this strategy we are not going to use the plus plus plus or minus minus minus. So, we are going to use the V z 0 0 0 and indicate the V z 0 here. Next we have V zs 1, that is this small vector V zs 1. Now V zs 1, what it means? How are we getting this vector? V zs 1 is formed by switching plus 0 0 and 0 minus minus that is plus 0 0 and 0 minus minus for half duration of time ok.

So, this is how V zs 1 vector is formed. V zL 1, this vector is formed by switching plus minus minus. V zL 2 is formed by switching plus plus minus ok. V zs 2 is formed by switching half of plus plus 0, this one and 0 0 minus, this one ok, half of. Now the important part, V zM 1, this vector. How are we generating this vector? We are generating by switching one third of 0 minus minus that is this one, plus 0 minus that is this one and plus plus 0 that is this one ok.

So, by switching plus plus 0, plus 0 minus and 0 minus minus for one third durations of time we get the V zM 1 vector ok. So, now, in our sector we do not have this vector. You can argue that ok. We are utilizing this vector, but we are not specifying that there is a vector here ok. Instead, we are saying that these black circles are our available vectors in this sector. So, we are redefining the space vectors in this sector ok.

And what is our redefinition or what is our new definition. The new definition is given by this and how are we defining these vectors? We are differing these vectors by using these switching state combinations. The most important one is this vector V zM 1 which is defined by saying that we will use these 3 vectors for one third durations of time ok. So, this is the new definition.

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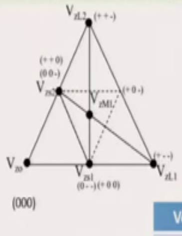
Another strategy for midpoint voltage balancing



- What is the effect on the midpoint voltage, assuming the switching period is sufficiently small so that three phase currents are almost constant?

Vector	How it is switched	Effect on midpoint voltage
V_{z0}	'000'	0
V_{zs1}	½{' + 00' + '0 − −'}	$½\{-i_A + i_A\} = 0$
V_{zL1}	' + − −'	0
V_{zL2}	' + + −'	0
V_{zs2}	½{' + +0' + '00 −'}	$½\{-i_C + i_C\} = 0$
V_{zM1}	1/3{'0 − −' + ' + 0 −' + ' + +0'}	$1/3\{i_A + i_B + i_C\} = 0$

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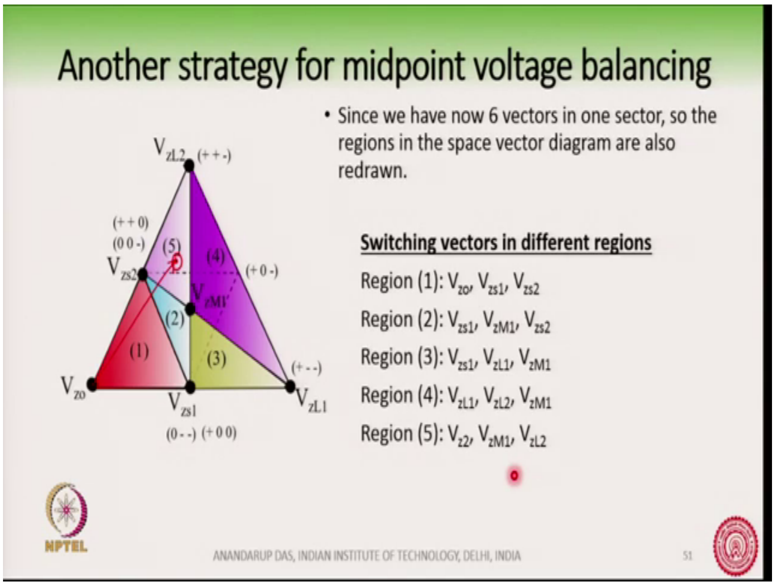

So, once we define these new vectors; therefore, what will happen? What will happen is, we will have a new set of regions ok, new set of regions in this sector ok. Earlier we had a different set of regions, if you see the conventional space vector diagram.

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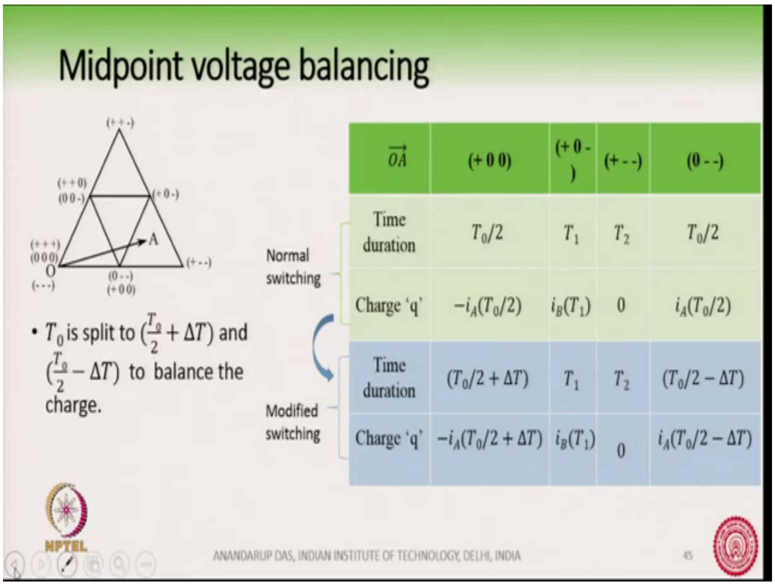

If you see, these are these where the regions there were 4 triangular regions in this sector. But now with this new definition; we will have 5 regions ok. These are colored in this and note that this is avoided. So, we have this region here 1, 2, 3, 4, 5 ok. Before we go into the regions and how we switch let us first see that how or why we have defined the vectors in this fashion ok. So, we have defined the vectors in this fashion. Let us see that after introducing this definition what is the effect on the midpoint voltage and that is what is the interesting.

So, let us see the effect on the midpoint voltage. So, again we assume that the T s period, switching period is sufficiently small. So, that all the currents are almost constant to their values ok. So, now, let us see what will be the effect on the midpoint voltage. If we apply the V z 0 vector, then of course, 0 0 0 and i A plus i B plus i C assumed to be 0, then the effect of the midpoint voltage is 0.

If we use V zs 1, as I as we have defined V zs 1 is defined as half of plus 0 0 and 0 minus minus these 2 switching states combined half of them, applying half of them, half of these switching states. So, in plus 0 0, we have seen that we have minus i A as the midpoint current and with 0 minus minus, we have plus i A as the midpoint current.

So, if I apply this new vector V zs 1, we will have a net current 0 ok. Net current 0. Again V zL 1, we know that when I apply plus 0 0, there is no effect on the midpoint voltage. When we apply V zL 2 similarly there is no effect on the midpoint voltage these 2 are large vectors.

When we apply V zs 2 that is this one, again we apply plus plus 0 and 0 0 minus for half durations of time. So, as to create V zs 2 and so its effect is again 0 half of minus i C plus i C and is equal to 0. We could have also said that t 1 and t 2 periods here, but anyway half of minus i C plus i C and that is equal to 0.

Now, you see the effect of V zM 1. Now you will see why V zM 1 has been defined in this particular fashion. So, if you see V zM 1, this vector how have we defined it? We are switching one third of 0 minus minus this one, plus 0 minus this one and plus plus 0 this one, one third of this this this.

Now, what is the midpoint current with 0 minus minus? With 0 minus minus, the midpoint current is i A. With plus 0 minus, what is the midpoint current? i B. That was the problematic case. If you remember, this was the problematic case, i B was flowing out of the midpoint. And then with plus plus 0, what is the midpoint current it is i C.

So, if I apply V zM 1 with this combination, the net current which we are taking out of the midpoint is again coming out to be 0. And so, again assuming that the currents are sufficiently constant in a switching cycle. So, therefore, we see that the application of V zM 1, if we apply V zM 1 or if we apply any of these vectors, if we apply any of these vectors then, we will never cause any fluctuation or very small fluctuation on the midpoint voltage ok.

So, if so, now, we are changing the space vector diagram by introducing additional vectors and the most important one is the virtual vector V zM 1. By introducing these additional vectors, what we are doing? We are ensuring that whenever we use these vectors; their effect on the midpoint voltage is 0 or minimum ok.

So, the concept of this virtual space vector highly simplifies this problem and it almost solves the problem. Now this also you can see as compared to the first technique that we discussed this technique can be applied at any modulation index ok. Because, now the whole space vector has been redefined. Whole space vector diagram has been redefined and so, this will be applicable for any modulation index.

So, once we have redefined the space vector diagram with new virtual vectors we have to also redefine the regions which are covering these space vector. So, as I told you, we always whatever may be the reference vector. So, if the reference vector is, if the reference vector is here we will always switch the three nearest enclosing vectors right.

So, with the help in presence of these virtual vectors; now we are redefining the sector with 5 regions instead of 4 regions earlier ok. And what are these regions you can see the these boundaries of these regions are shown in the diagram. So, in region 1, for example, the enclosing vectors are for region 1 here the enclosing vectors are V z 0, V zs 1, V zs 2 like this.

For region 2; the enclosing vectors are V zs 1, V zM 1 and V zs 2, like this. For region 3; this are the 3 enclosing vectors. For region 4; these are the 3 enclosing vectors and for region 5; these are the 3 enclosing space vectors and this is shown here.

So, when the reference vector is here, we will for example, if the reference vector is here we will switch. So, it is in region 5, we will switch V zM 1, V zL 2 and V zs 2 ok. Now again the same principle of volt second balance we will apply here also ok. So, we will see that by applying volt second balance we can be able to realize the reference vector ok.

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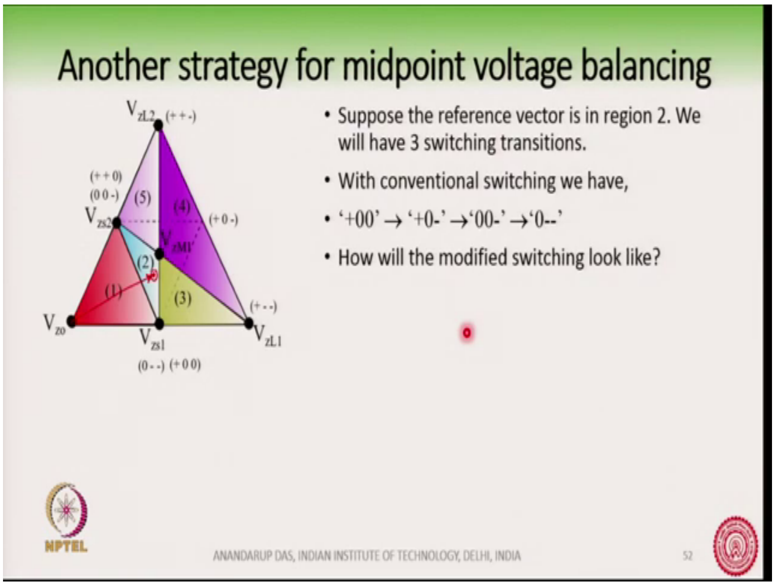

Now, one question that will automatically come up now in your mind is that; this V zM 1 is a combination of 3 vectors ok. V zM 1 is not a vector which is obtained from a direct switching. V zM 1 is obtained by switching of one third of these 3 vectors here. So, will it not increase the switching frequency? Yes, indeed it will be increasing the switching frequency and that is correct.

By use of this V zM 1, the switching frequency. In fact, increases by about 33 percent. However, the midpoint voltage fluctuation has or is highly minimized with this technique. So, we can see how the modified switching will look like with this kind of a virtual vector. How will it look like?

So, with conventional switching reference vector is somewhere in here. Suppose, the reference vector is here ok. So, we will now see or compare how much will be the extra switching due to the virtual vector ok. What happens in a conventional space vector PWM for NPC and what happens when we introduce this virtual vector. If we had used conventional switching to realize this vector what would have what we would have done. We would have done this for this one, you would have done say plus 0 0, plus 0 0 and plus 0 minus, plus 0 minus, then going to 0 0 minus, this one and again coming back to 0 minus minus.

So, for realizing this reference vector in conventional switching we would have used these 3 vectors with such a switching sequence. And in this switching sequence every time there is one change of or 1 transition of. So, plus 0 0 to plus 0 minus means C phase is changing from 0 to minus ok. Now, let us see what happens with the use of the V zM 1, how can we make a modified switching.

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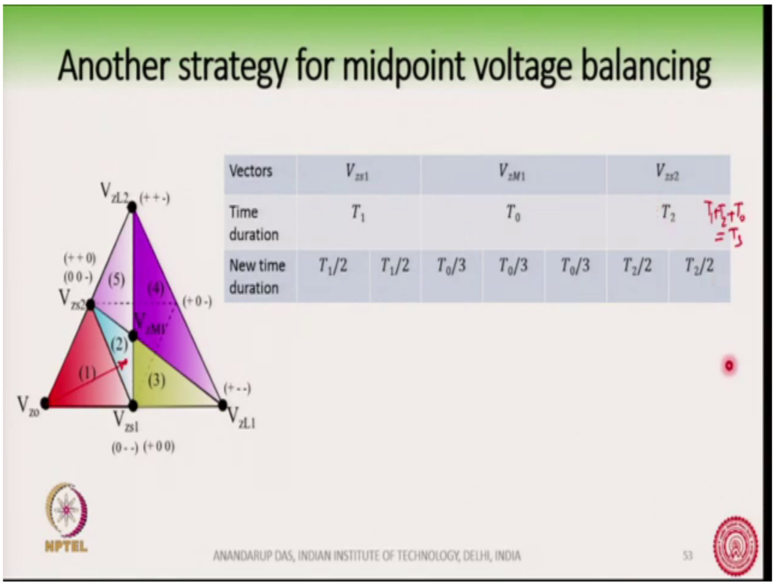

So, in order to fully understand the V zM 1, what we will do here; you see this is kind of a slightly advanced PWM technique, but we introduced, I introduced this to you because you see what are the possibilities with PWM. So, advanced with advanced PWM, many possibilities open up and. So, I would like you to introduce you to this advanced slightly advanced PWM techniques.

So, when the reference vector is here in this place then, what happens see we define that V zs 1, V zs 1 is switched for T 1 duration ok. So, this 1 is switched for T 1 duration. V zM 1 is switched for T 0 duration and V zs 2 is switched for T 2 duration. So, that we know that T 1 plus T 2 plus T s. So, T 1 plus T 2 plus t 0 is equal to T s, the total time period.

Now, before so, what we do before I switch the V zM 1, first I will divide this T 1 into 2 parts. T 1 by 2 and T 1 by 2. T 0 into 3 parts; T 0 by 3, T 0 by 3, T 0 by 3 and T 2 into 2 parts; T 2 by 2 and t 2 by 2. So, I am splitting the timing duration and we will apply the vectors space vectors in a clever fashion. But first we have split the timing durations into several such sub parts.

So, T 1 is split into T 1 and T 1 by 2 and T 1 by 2, T 0 is split into T 0 by 3, T 0 by 3, T 0 by 3 and T 2 is split into T 2 by 2 and T 2 by 2 fine.

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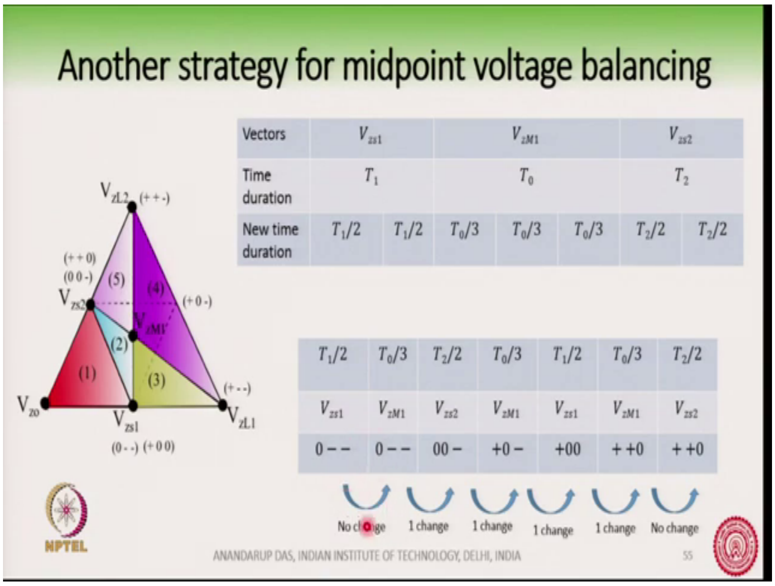

Next, how am I going to apply the vectors? So, we will now place these timings in a different fashion, not in this sequence ok. So, you see how we are going to place the timings first. So, this T 1 by 2 comes here, but then I have a T 0 by 3 time which I go from here to here.

Then I put a T 2 by 2 timing here, then I put another T 0 by 3 here, then T 1 by 2 here, T 0 by 3 here and another T 2 by 2 here. So, you see that in a switching cycle placing of these vectors can be done like the timings can be interchanged. Of course, this will create a poorer harmonic performance. We understand that it will create a poorer harmonic performance.

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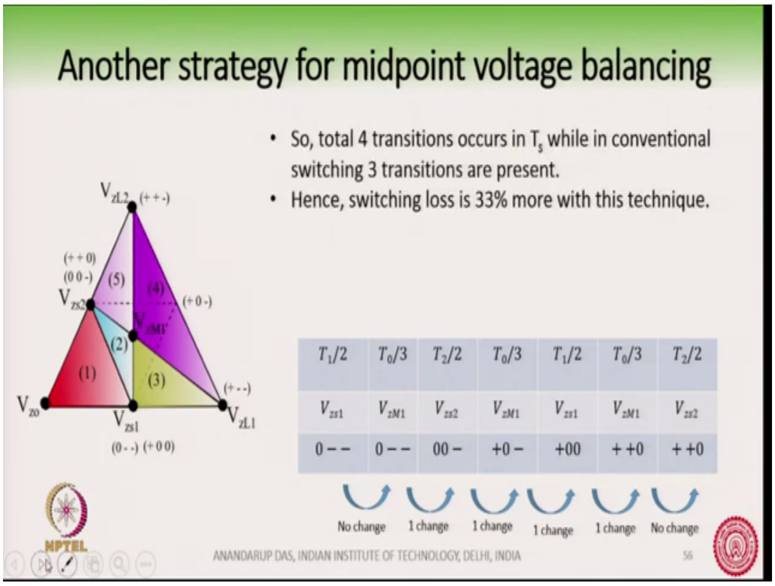

However, if the switching frequency is sufficiently high which is most of the case in applicable, then this poorer harmonic performance may be acceptable it should not be any problem because if the fs or because in this case the harmonics will recited 2 fs. So, in that 2 fs we can filter it out the harmonics.

So, but now what we are doing, we are redistributing these time periods in a different fashion ok. Now what we are doing in this t 1 by 2 period; I will applied V zs 1 vector. In this T 0 by 3 period, I will apply V zM 1, in the T 2 by 2 period; I will applied V zs 2 and similarly, V zM 1, V zs 1, V zM 1 and V zs 2 corresponding to this table here ok. Corresponding to this table I will apply the vectors here.

Now, so, if you remember I told you that V zs 1 was half of 0 minus minus and plus 0 0. If you remember V zs 1, V zs 1 was half of plus 0 0 and 0 minus minus. So, this 0 minus minus and plus 0 0 are here ok. That half so, this is half of 0 minus minus and half of plus 0 0 ok. So, this 2 are here.

Similarly, V zM 1 was one third of 0 minus minus, plus 0 minus and plus plus 0. One third of 0 minus minus, plus 0 minus and plus plus 0. So, 0 minus so, this is one third, one third, one third here ok. And V zs 2 was half of 0 0 minus and plus plus 0. These 2 half of so, this is how this is done ok. So, if you do like this if you place your switchings like this, what happens with the changes from here to here you see there is no change, there is no switching change identical.

From 0 minus minus to 0 0 minus, you have one change. From plus 0 minus from this to this you have one change, 0 0 minus to plus 0 minus means; you have the plus changing from 0 so, one change. And then from here to here you have one change, from here to here you have another change and for the last one there is no change.

So, therefore, you see that there are 4 changes happening in a T s period. Why using this strategy of virtual space vectors ok. So, there has been 4 switching transitions which if I had used the earlier one, there were 3 transitions. If I had used this one, there were 3 transitions, but now we have 4 transitions ok. And so, we have about 33 percent more switching losses with this technique ok.

However the advantage is that we are now able to minimize the midpoint voltage fluctuations ok. And this also shows that how we can play around with the vectors and the placement of the vectors in a switching cycle T s ok. You can place these vectors in different ways ok.

You can also make the vectors one sided like discontinuous PWM. So, you can make the T 0 vector T 0, T 1, T 2; you can make T 0 by k or k times T 0 and 1 minus k times T 0 and then T 1 and T 2 you can make k 0 you can make k other values. So, in that way you can play around with the vectors and their timing durations and one way of doing is shown here ok. And in this way it is possible to do many things and one of them is like midpoint voltage fluctuation minimization.