High Power Multilevel Converters - Analysis, Design and Operational Issues
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Lecture – 09
Space Vector PWM using carriers

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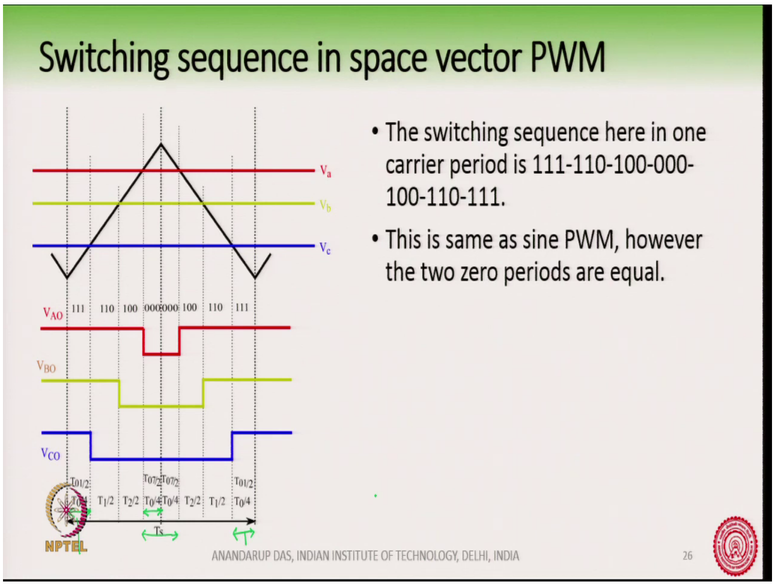

So, let us now see what is the switching sequence in Space Vector PWM. So, in this is a repetition of what we have done earlier. In space vector PWM the same thing happens, the same switching sequence 1 111 0 110 100 000 100 110 and 111, the same switching sequence you can see here with a b c reference waveforms.

The same switching sequence as sine PWM, the difference is that this period here that this period here and this period here these two periods are equal ok. That means this period here and the sum of this plus this period, these two sum, the sum of these two they are equal. So, this is what makes the space vector PWM different than sine PWM, where it is always ensured that the zero periods at the beginning and at the end are equal in a sub-cycle.

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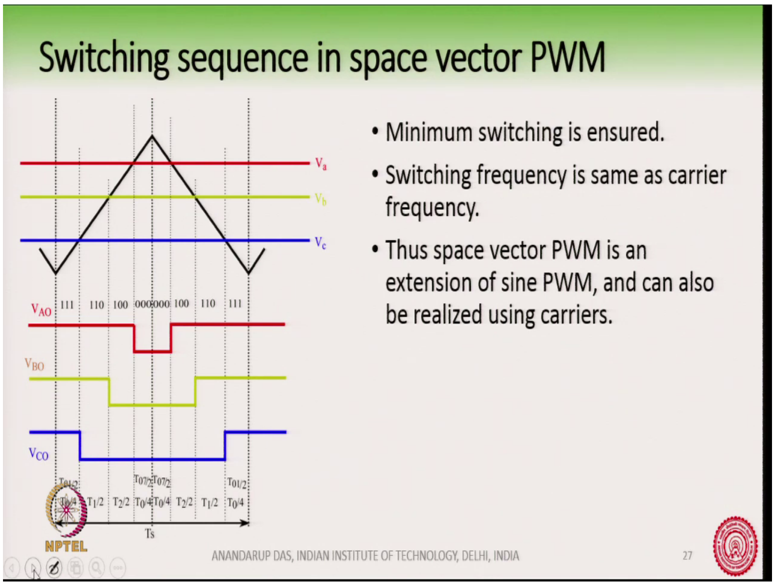

Of course, with space vector PWM from the switching sequence itself, we can see that the minimum switching sequence is ensured, minimum switching is ensured same like sine PWM. And, the switching frequency is same as carrier frequency like sine PWM; here also we can see that the V AO voltage has the same switching frequency like the carrier frequency. For example: V AO here is from 1 it is going to 0 and again going to 1.

So, this makes it like 1, it is switching one time in this carrier period; it goes from 1 goes to 0 and then comes back to 1, means the top switch is switching once and the bottom switch is also switching once. So, the top switch was on here it goes to off and then turns on again, while the bottom switch is off here, turns on here and then again turns on here that turns off here. So, the each switch in phase a has the same switching frequency equal to the carrier frequency.

So, for the b phase also the same logic happens and for the c phase also the same logic happens. So, switching frequency of devices in the converter is same as the carrier frequency. So, by observing the switching pattern, the minimum switching; the switching frequency everything we can say that space vector PWM is an extension of sine PWM. And, probably it can also be realized using carriers, the only challenge which that we have now is to make the two zero vectors equal which is not happening with a sine PWM.

So, we have to make a strategy such that the starting and the ending vectors have equal duration and that we should do using carriers. If we can do that then space vector PWM can also be realized using 3 modulating wave forms and a carrier, without the need of any sector identification, without the need of any timing calculation etcetera. So, it can be very easily realized just by comparing 3 modulating wave forms and a high frequency carrier. So, let us see how we do it.

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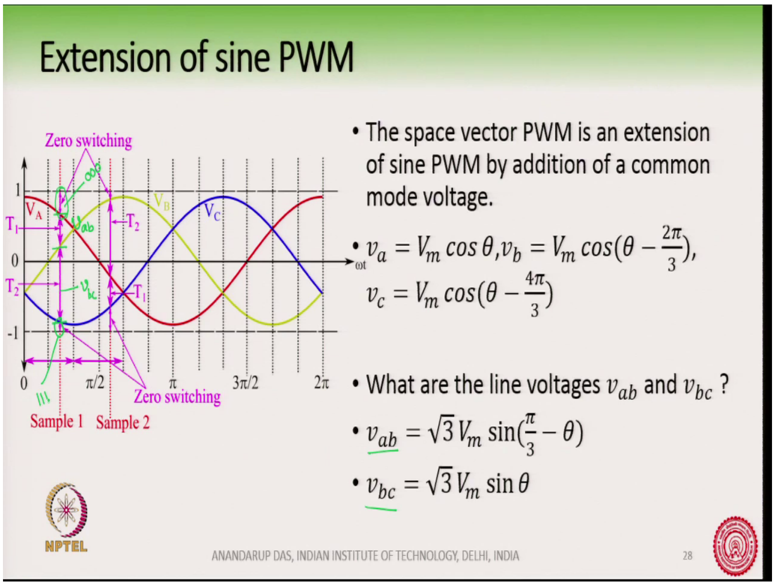

So, if we see carefully the sine PWM technique we see that so, these are the 3 modulating wave forms and the carrier, there is a high frequency carrier here which we have not shown in this in this particular diagram. Now, suppose the 3 modulating wave forms are denoted by 3 cosine waves as you can see here v a is V m cos theta v b is V m cos theta minus 2 pi by 3 and v c is equal to V m cos theta minus 4 pi by 3.

So, let us first see what are the line voltages v ab and v bc right. So, if you subtract v b from v a we get v ab which is root 3 V m sin pi by 3 minus theta and v bc is equal to root 3 V m sin theta. So, this v ab and v bc is on this diagram or on this waveform v ab corresponds to this distance here and v bc corresponds to this distance here. So, this this distance here is v bc because it is the instantaneous difference between phase b and phase c whereas, this distance here corresponds to v ab ok. It is the instantaneous difference between a and b phase waveforms.

So, this expression v ab and v bc here is representing the distance between the waveforms on the on the left hand side of the slides. Now, what are these distance is representing here and here? These distances if you can imagine the carrier here, if you can imagine there is a high frequency carrier here which I have not shown in this diagram. Suppose, when the carrier is here during this point all 3 phases, all 3 phases are higher than the carrier during this region all the 3 phases are higher. So, this must be place which corresponds to the 111 period, 111 switching state.

So, similarly this area here or this distance here must be because here you see that all the 3 modulating wave forms is less than the carrier in this region, this region here. So, this must be the distance which represents the 000 state ok, where all 3 modulating wave forms are less than the carrier. So, this one is representing the 000 state and this distance here is representing the 111 state and clearly the 000 state and 111 state at this time instant are unequal which is expected in sine PWM.

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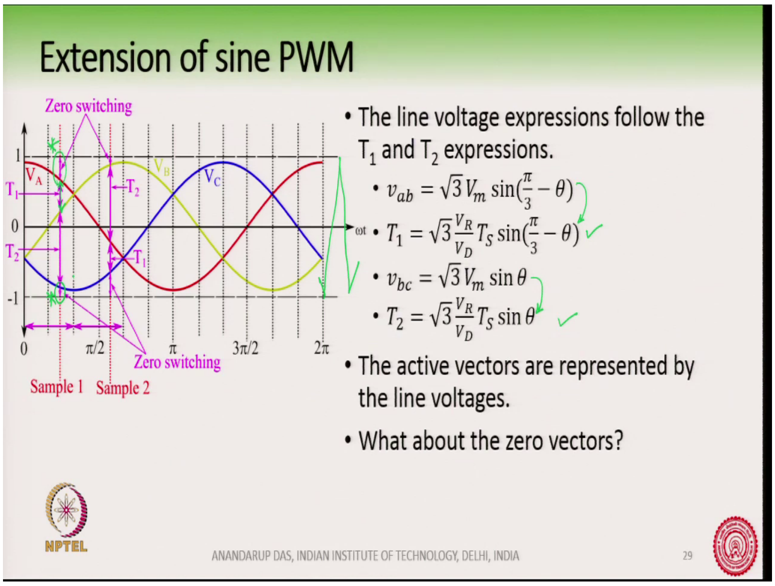

Now, what about v ab and v bc? If we see the T 1 and T 2 expressions which we had earlier derived, we see that T 1 is equal to this here and T 2 is equal to this expressions. And, if you observe the v ab and T 1 expressions they are very similar, you see except for the multiplying factor at the beginning. So, they have this sin pi by 3, both of them have the sin pi by 3 expression and there is a root 3 here. But, there is the multiplying factors are different. What about T 2 and v bc?

You see that V m sorry this sin theta and sin theta matches root 3 and root 3 matches, only this multiplying factor which can be termed as a scaling factor because, 1 v ab and v bc are voltages whereas, T 1 and T 2 are times ok. So, these scaling factors are same for both T 1 and T 2, but if we can use this scaling factor their expressions are very similar. So, therefore, we can say that this distance here, this distance here that is this one which is denoting v ab is actually representing T 1 whereas, this distance here is equal to v bc and is actually representing T 2 ok.

So, that is this one is representing this and this is representing this. So, the voltage v ab is actually representing T 1 and v bc is representing T 2 of course, this is in sector one. For other sectors, if you do the the same exercise I will recommend you to do the same exercise for other sectors; you will see that the T 2 and T 1 these expressions are interchanging. I will give this as a small exercise for you.

So, this and this here, this distance T 1 here and this distance T 2 here are proportional to the v ab and v bc voltages. And, these two the distance here and the distance here which we have earlier said is proportional to the zero vectors ok, see you can see here these are the zero vector; so, therefore, if we can center this waveform inside the carrier.

So, the carrier is here, if we can center the waveform inside the carrier such that the distance here; this distance here and this distance here these two distances are always equal from this plus 1 and minus 1. Then we can make sure that the two zero vectors are equal ok, that is by positioning the waveform, this a b c waveforms at the center between 1 and minus 1. If we can position them then we can make sure that this zero vector here and the zero vector here are always equal ok.

Of course we when we do this, we cannot change T 1 and T 2 vectors because, if we change T 1 and T 2 vectors then we are going to destroy the volt second balance equation; we cannot change T 1 and T 2. What we are changing is the T 01 and T 07, those two vectors that their timing duration is only what we can manipulate. And, we are trying to make them equal without touching T 1 and T 2 vectors or their T T 1 and T 2 time in durations for v 1 and v 2 vectors in sector 1.

So, the whole idea, now the whole challenge will be how to center the a b c waveforms inside the carrier such that the two zero vectors have equal timing duration on the top and on the bottom.

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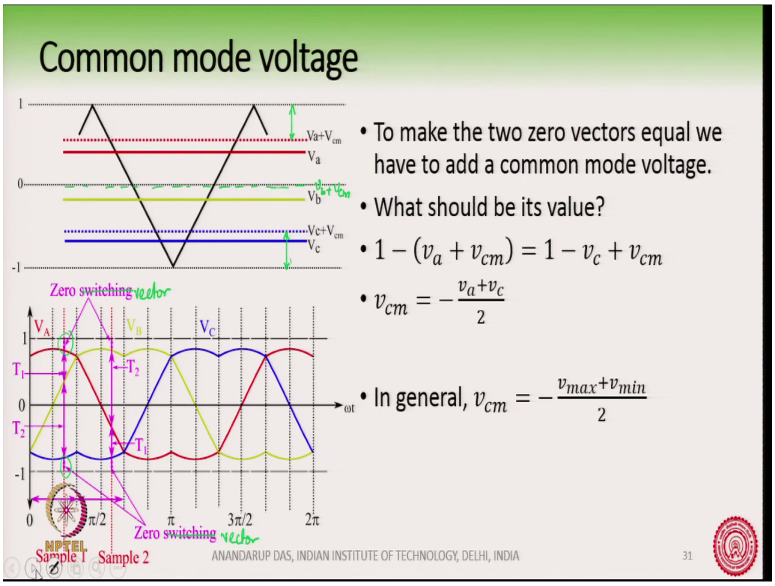

So, this is shown in this figure; here a phase, b phase and c phase are shown here and we are adding a common mode voltage ok. Why we are adding a common mode voltage? Because, we do not want to change the active vector durations, we do not want to change that T 1 and T 2, but we would like to make sure that the distance here and the distance here, they are same. That means, the maximum the height of the maximum waveform from plus 1 or the distance of the maximum from plus 1 and the distance of the minimum from minus 1; these two distances represented by these two green arrows must be equal.

So, we are basically here shifting the whole waveform up or down which is indicate which indicates we are adding a common mode voltage, we are adding the same thing through all the 3 phases. So, what is missing here? There is something missing here which I am adding now is this V b plus V cm, it is missing in this. So, we have added so, original waveform was V a V b and V c and we have added a same common mode voltage. So, it becomes V a plus

V cm V b plus V cm and V c plus V cm ok; so, that the length of these two arrows, the length this distance and this distance here become equal. So, what should be the common mode voltage?

So, if you just do the geometry; so, 1 minus v a plus v cm that is this distance must be equal to 1 minus v c plus v cm that is this distance. So, v cm is equal to minus of v a plus v c divided by 2 for this example ok. In this example V a was the maximum waveform and V c was the minimum waveform ok, this happens in sector 1. So, this v cm was minus of v a plus v c divided by 2, for any other sector the general v cm formula is minus of v max plus v min divided by 2 ok; minus of v max plus v min divided by 2. So, if we add this common mode voltage to the 3 reference waveforms all the time, we are making sure that at all points of time the distance of the maximum waveform and the minimum waveform from plus 1 and minus 1, the distance are always equal.

Thereby, ensuring that the zero vector here and the zero vector here are always equal ok. This equal division of the zero vector will make sure that space vector PWM has been achieved and this is nothing, but an extension of the sin PWM by adding this v cm voltage, adding this common mode voltage. So, once you add the common mode voltage, you can see here that the after adding the common mode voltage the waveform looks like here, looks like this is what is shown; where this zero vector this and this here they are they are equal ok.

So, this is not switching, this is zero vector and this is also zero vector, I think this is also zero vector. But, when we add the common mode remember that T 1 and T 2 is not changing because, T 1 is line voltage; T 1 is proportional to the line voltage, v ab and we have added the same common mode to both a and b phases. So, T 1 does not change, v ab does not change, T 2 does not change, v bc also does not change. So, T 1 and T 2 are not changed in magnitudes.

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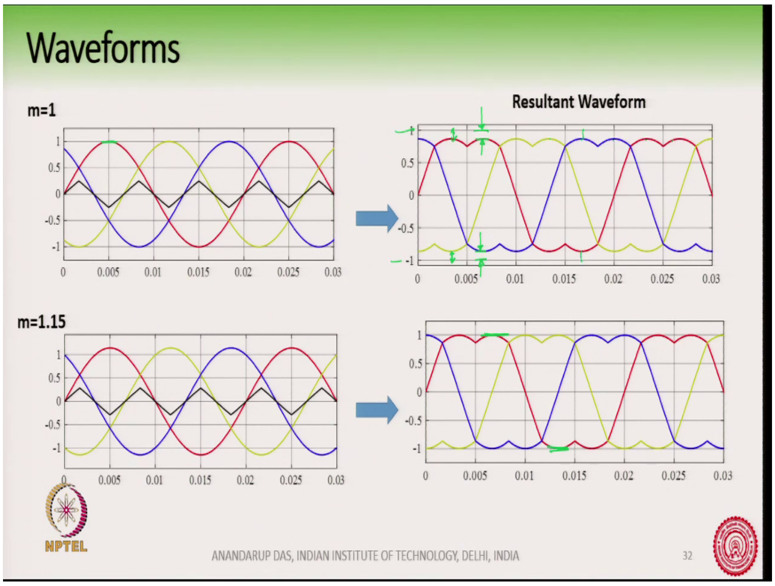

Then we see the resultant wave form, once we have added the common mode voltage. So, suppose we have a modulation index of 1, like sin PWM. So, these 3 are the 3 sine waves and they have touched 1 here. We can see that they have touched 1, now if we add this common mode voltage given by v max minus minus of v max plus v min divided by 2 which is this waveform, the black one here. If I add this one then we see that the resultant wave form becomes like this ok. And so, in this resultant wave form this distance and this distance are always equal that is the zero period ok.

But, we also observed that now we have been here we our sin wave was touching 1. So, we were at the end of the linear modulation, but by adding this common mode voltage; we have actually we have got some extra space here. This is the space, extra region which I have got now ok, by adding the common mode voltage. So, it is possible for us to go beyond m equal to 1 modulation index which is shown on this diagram here. So, here we have gone up to 15 percent more that is m equal to 1.15 where we see that the sine wave has crossed one line ok.

But, after adding this common mode voltage which is minus of v max plus v min by 2, we see that the resultant waveform is between plus 1 and minus 1. The resultant waveform is between plus 1 and minus 1 showing that at m equal to 1.15 we are now reaching the end of the linear modulation. So, this is the advantage of adding the common mode voltage that not only it makes sure that the zero periods are equal, but it also centers the waveform between two carriers. You can see the addition of the common mode voltage has centered this waveform, these waveforms between the two carriers. So, this is the two carriers so, the waveform has been now centered between the carrier.

The carrier is spanning between plus 1 and minus 1, at all points of time; at all points of time as you can see here or here or here. Any point you take the distance from plus 1 and the distance from minus 1 is always equal. So, which means we are always ensuring that the carrier, the 3 waveforms are middle of the carrier ok.

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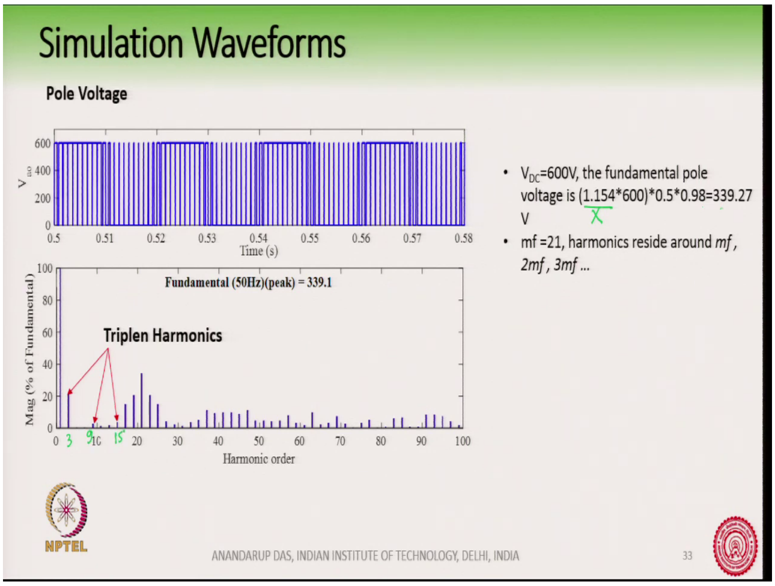

So, we have done some simulations with this space vector PWM and you can see for example, suppose we have V DC equal to 600 volt, the fundamental pole voltage with if you use space vector PWM with a modulation index of 0.98. So, the magnitude of voltage that you can get is 1.15 or 1.154 into 600 into 0.5 into 0.98 that is 339 volts. In case of sine PWM we were not getting this one, in sine PWM this 1.15 was not available. So, in space vector PWM we get this much voltage extra.

If you see the harmonic spectrum, if you have the fundamental here which is again 339 volts and then you have actually all triplen harmonics, triplen harmonics means 3rd, 9th, 15th, 21st etcetera. So, you see here this is the 3rd harmonic, this is the 9th harmonic, this is the 15th harmonic and so on. So, all these harmonics will come and this is the harmonic that is introduced by the common mode voltage 3rd, 9th, 15th, 21st etcetera.

They are being introduced by the common mode voltage, but this will appear on the pole voltage. But, it will never appear on the line voltage neither will it appear on the load voltage. Because, line voltage is the differential voltage between two pole voltages V AO and V BO. So, v ab is nothing, but V AO minus V BO; so, it is a differential voltage. And so, the common mode voltage will get out.

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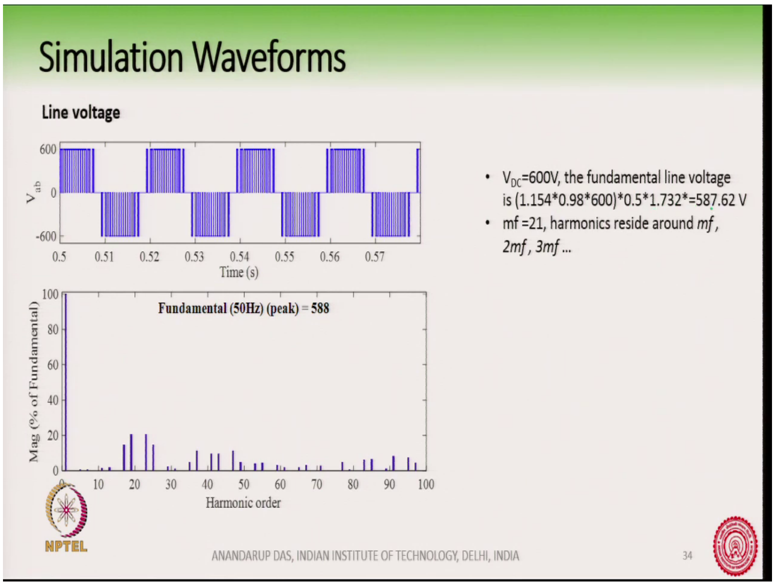

So, you can see the line voltage and you see in the line voltage spectrum there is no 3rd harmonic. So, there is no 3rd harmonic, there is no 9th harmonic, there is no 15th harmonic like that. So, all these have disappeared. So, the line voltage magnitude is root 3 times the old voltage magnitude. So, it is 587 or more like 588 volts.

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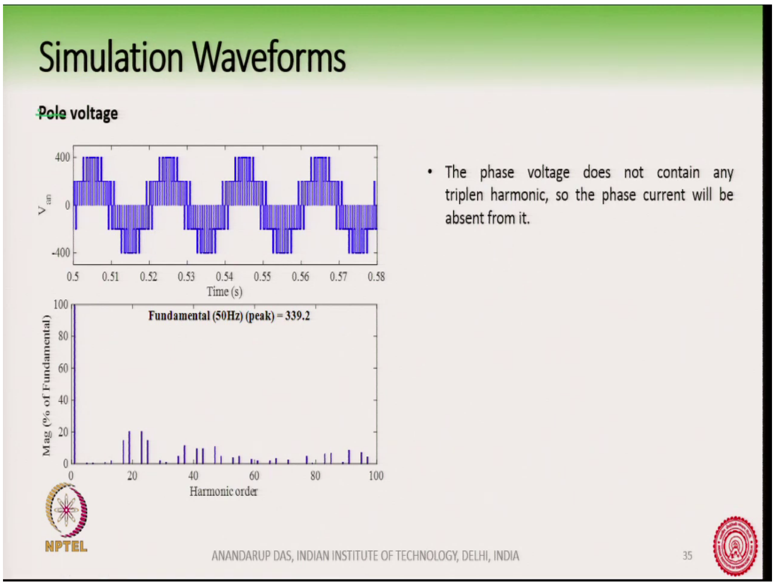

And, since the line voltage does not contain any triplen harmonics; so, the phase voltages will also not contain any triplen harmonics. So, this is not pole voltage, this is phase voltage here. So, the phase voltage will not contain or load phase voltage will not contain any harmonics. So, we see that in space vector PWM to summarize, we see that space vector PWM is nothing, but an extension of sine PWM, where the two zero vectors are used equally.

It can be realized by carriers just like sine PWM there is no difference, only thing is that we have to adjust the common mode, we have to introduce a common mode voltage. We have to adjust it such that the zero vectors at the start and at the end are equal in duration. And, the greatest benefit of space vector PWM over sine PWM is that we get 15 percent more from the same DC bus which was not possible in sine PWM technique.