Pulsewidth Modulation for Power Electronic Converters

Prof. G. Narayanan
Department of Electrical Engineering
Indian Institute of Science, Bangalore

Lecture - 22
Space vector based advanced bus-clamping PWM

Welcome back to this lecture series on Pulsewidth Modulation for Power Electronic Converters. So, this is we have been looking at this you know we have been going through different aspects of this particular course, pulsewidth modulation for power electronic converters. And now we have been looking at space vector based pulsewidth modulation for three-phase voltage source converters now.

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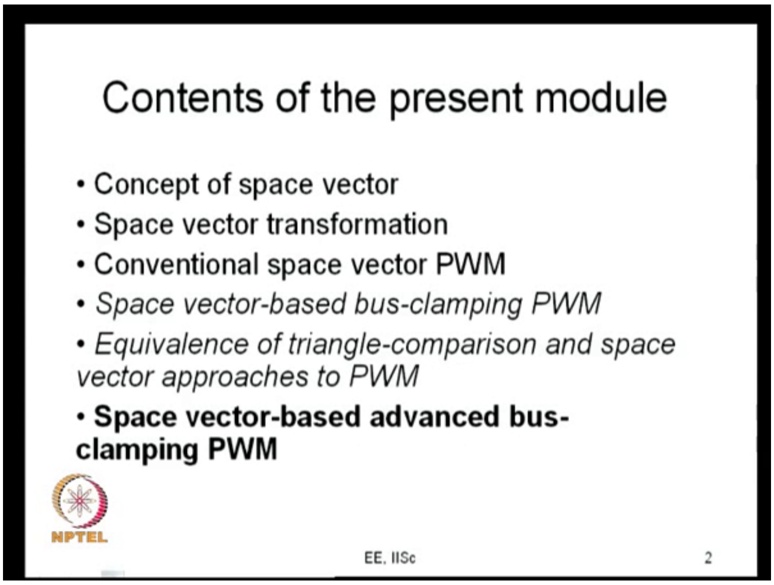

So, the present module has actually been focusing on space vector based pulsewidth modulation and we earlier covered the concept of space vector what exactly mean by space vector and we need space vector transformation, how can it transform three-phase voltages are currents into space vector mean. Then we have been dealing with space vector based pulsewidth modulation. And we particularly dealt with conventional space vector pulsewidth modulation, which is a very very popular method quite similar to sine triangle PWM. And then we have also been looking at several bus clamping PWM methods which are equivalent to the discontinuous modulation schemes that we discussed before in the triangle comparison module.

So, we also looked at space vector based bus clamping PWM, and we have also been seeing the equivalence of triangle comparison and space vector approaches to pulsewidth modulation. So, today we will do a bit of these two again, we would have a review and we would take a look at bus clamping PWM at maybe at a slightly greater depth than we did in the last lecture. And we will also try and see how exactly you know we you know the similarities between these two methods of triangle comparison and space vector approach. And we will go beyond the similarities as I have been tazed telling you space vector approach is actually a little more general than triangle comparison approach; certain things which are possible with space vector or not possible with triangle comparison almost everything that the triangle comparison can do space vector approach can also do.

So, whatever PWM wave forms can be produced using the space of a triangle comparison approach, can also be produced using the space vector approach whereas, the conversions probably not true I mean there are certain pulsewidth modulation methods which are based on the space vector idea, they are not possible using the triangle comparison method. So, some such methods are is advanced bus clamping PWM and that is what we would be emphasizing on today right.

So, let us just get started with the present lecture, which is primarily on space vector based advanced bus clamping PWM and if you know advanced bus clamping PWM you know you should really know what is bus clamping PWM which we discussed in the last class. So, we will get into more details of bus clamping PWM before eventually covering this, what we mean by this advanced aspect of bus clamping PWM. To put it in a nutshell what we are going to look at by means of you know bus clamping PWM is, you have the situation where one of the phases is clamped on one of the dc buses for some period of time. Say for example, every phase would be clamped to the positive dc bus for 60 degrees and negative dc bus for 60 degrees and that is why you would call it as bus clamping, what is getting clamped a phase is getting clamped to a dc bus.

So, for 60 degree during the positive half cycle and 60 degree during the negative half cycle typically in that you would call as a bus clamping PWM method. In advanced bus clamping PWM method a similar bus clamping will occur in addition to that, some phases will switch at twice the nominal frequency. You will have a situation where a phase switches at the switching frequency at twice the nominal frequency and also at the switching frequency. So, that is why we have this term advanced bus clamping PWM.

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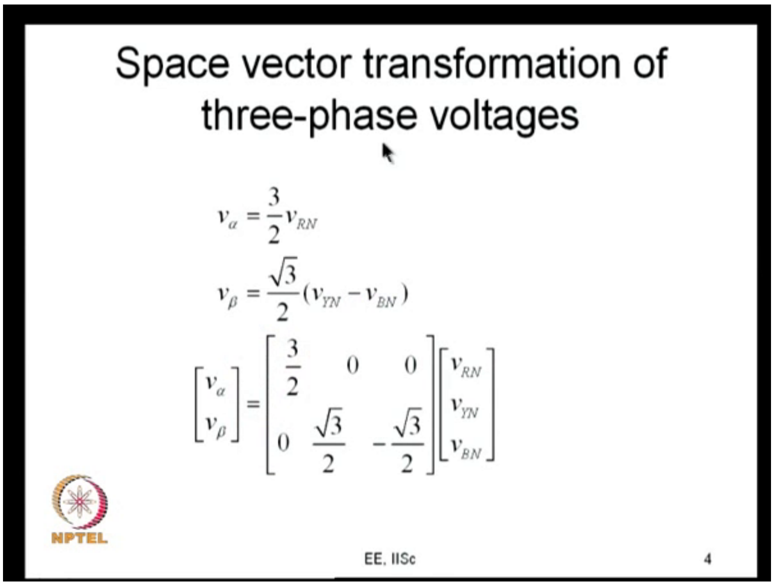

And now here we go back to the space vector transformation of three-phase voltages will quickly look at in what is this transformation, we have known this you know we have been doing this over the last 3 classes. So, v alpha is equal to 3 by 2 times v RN and v beta is root 3 by 2 times v YN minus v BN, this is where space vector transformation right and the same thing has been written in the matrix form here.

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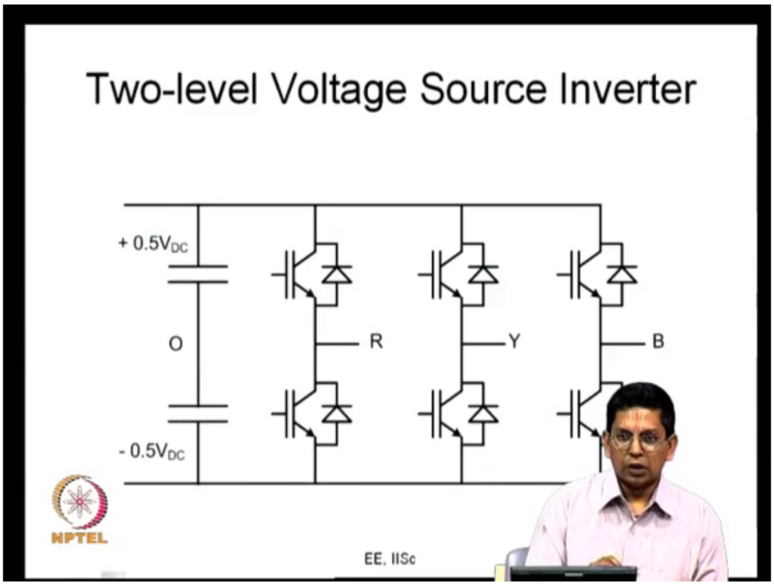

So, now you have a voltage source convertor and voltage in every leg is a single pole double throw switch R Y and B are the midpoints of the legs and the 3 load terminals are connected here, and you know you have depending on whether the top is one or the bottom is on V R O s plus 0.5, V DC or minus 0.5 V DC. Similarly with Y phase and B phase and you have 8 different inverter states that are available, and the 2 states here produce 0 there are 0 states on all the top are one and all the bottom are on its 0 state, all the other states are called active states, right.

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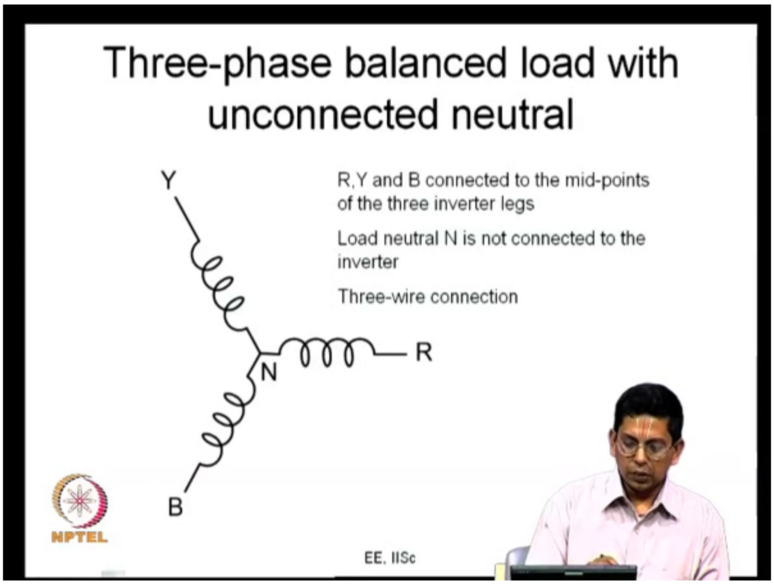

So, know about the regarding the load we have the load R Y and B connected like this and the neutral point N is not electrically connected anywhere else except through the windings to these terminals. So, we are looking at a three-wire connection you know that is how the load is now.

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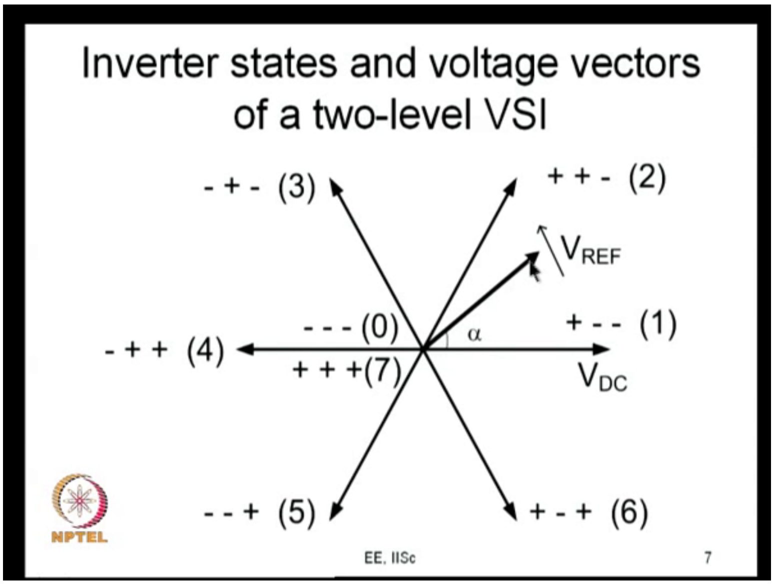

And in this kind of a scenario what we are doing is. So, we have these are the vectors. So, there are 8 inverter states as I mentioned to you and when the inverter is in the state plus minus minus for example, what we mean by that is the R phase top device on y phase bottom is on and the B phase bottom is on, under such condition what happens is the inverter up place this is the voltage vector now, that is there is some V R O is plus V DC by 2, V Y0 is minus V DC by 2 and V B0 is minus V DC by 2 and this can this produce a certain sets of three-phase voltage is v RN, v YN, v BN applied on the load and that in turn produces a voltage vector shown like this.

And the 6 active states produce six active vectors which are shown like this, all are of magnitude V DC and they are separated by angle 60 degrees as we shown here. And what we do here in space vector by s w m there is a revolving reference vector, instead of three-phase sinusoidal wave you use a voltage vector and the voltage vector is revolving it revolves at the modulation frequency it has a constant magnitude under study state, we sample it every time and this is how the samples will look over a cycle, right.

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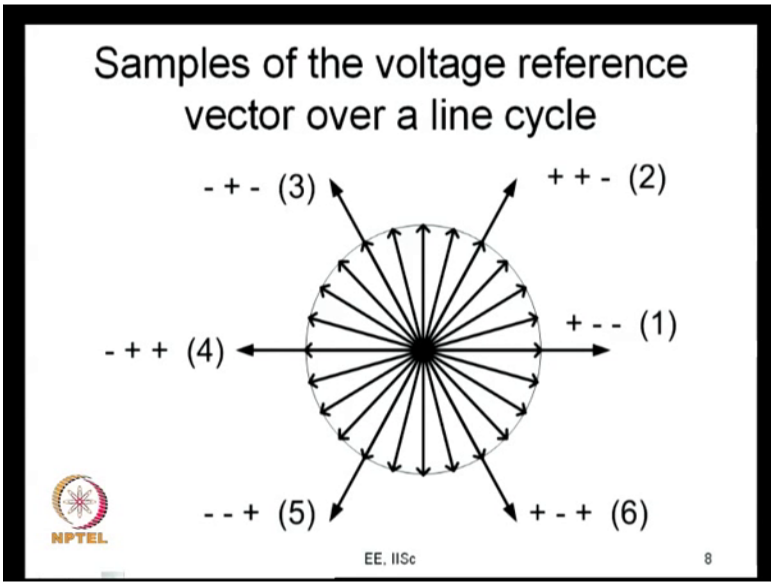

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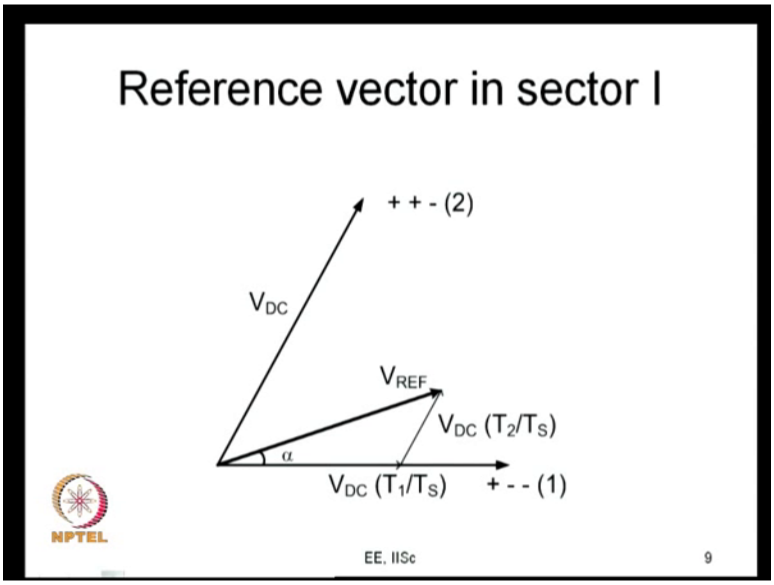

Then you consider a particular sample, there is a particular sampling interval or a sub cycle duration time T s and within the T s let us say if this is what is your reference vector commanded and this reference vector falls between vector 1 and vector 2; so between vector 1 and vector 2. So, that the active vectors v 1 and v 2 are used and in a in addition to this null vector 0 to produce this particular vector of magnitude V REF in angle alpha. So, you do this by applying the active vector 1 for T 1 duration within T s and the active vector v 2 for T 2 duration within T s, and the null vector for the remaining duration T z and you get a resultant vector which is equal to the commanded reference vector.

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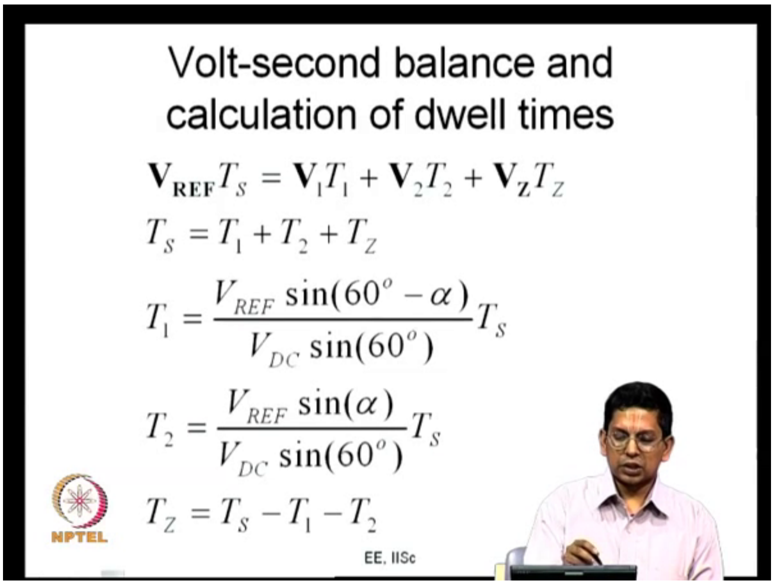

So, that is the equations here, this is the commanded reference vector and this is the applied vector here and the active vector 1 is to be applied for duration T 1, and active vector 2 for T 2 and null vector for T z how do you calculate T 1 T 2 and T z? You get them here, this is T 1 in terms of V REF in alpha T 2 in terms of V REF in alpha and T z that is T s minus T 1 minus T 2, we have seen this in the last 2 3 lectures just having a quick brush throw fall that now.

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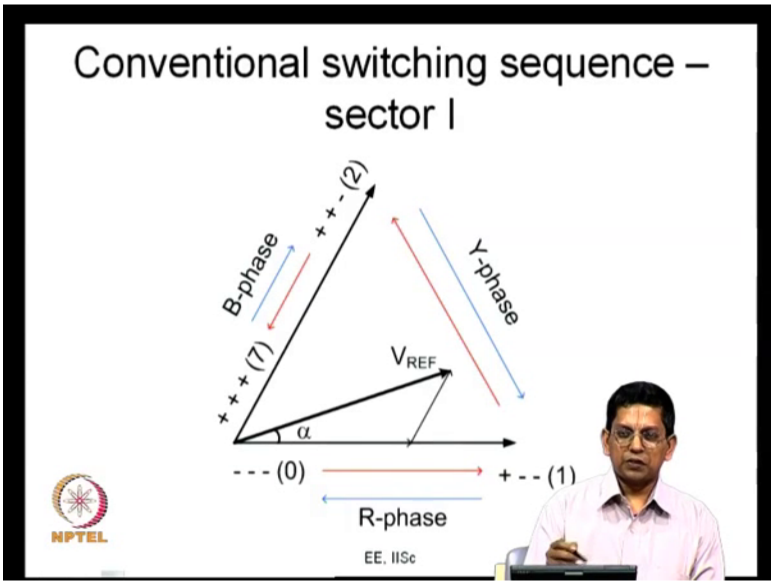

And when the conventional switching sequence are in conventional space vector PWM what we do is you apply the null vector, you start with the null vector go to active vector 1 2 and come back to the null vector. So, when you do this the null vector is seen the first instance null vectors applied using the zero state minus minus minus, at the last instance in null vector is applied during the using the zero state plus plus plus. So, you for example, you start with minus minus minus all the bottom device on switch R phase, then you go to the active vector and you apply this for a duration T 1, and then you switch your Y phase and you go to active vector 2 and you stay here for duration T 2 and then you switch B and you go here and stay for duration B now.

So, you can go back to the previous lectures in case you have any further any this thing on that. So, this is what we have been looking at and in the next sub cycle you will come back. So, you start from a zero state go to active state 1 active state another active state and then to the other zero state and you come back this is the now conventional switching sequence now.

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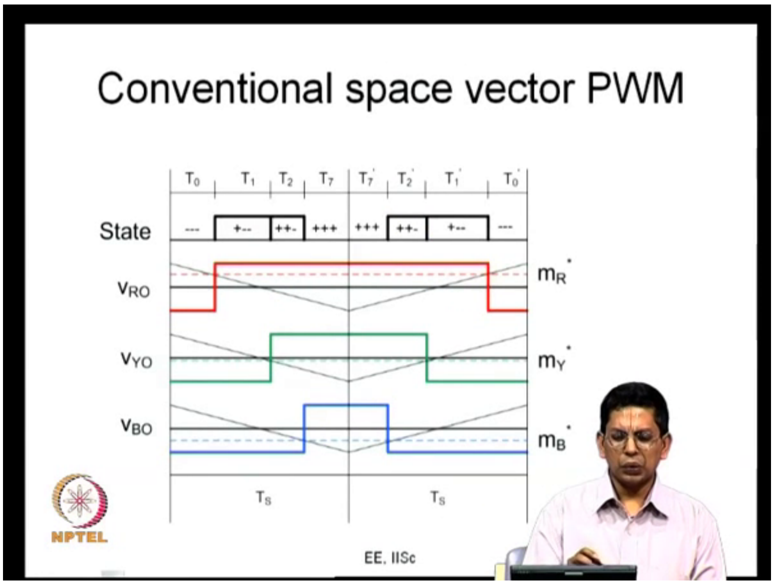

So, this is what is shown in with against time, this is the inverter state up right against time. You have inverter state 0 minus minus minus, you have inverter state plus minus minus, you have inverter state plus plus minus and plus plus plus these are applied for durations T 0, T 1, T 2 and T 7 respectively as shown here now, right.

So, in the next sub cycle they are applied in the reverse sequence 7 2 1 and 0 plus plus plus is applied first, plus plus minus next and plus minus minus and then minus minus minus. So, the states are applied in the reverse sequence right. So, these are the pole voltages as we saw and we also saw the equivalence now. So, the pole voltages are like this and if that is the pole voltage the dash line indicates the average pole voltage and the scale diversion of the average pole voltage is m R star, similarly the scaled version of the pole volt average pole voltage is V Y0 average and V B0 average would be m Y star an m B star. Now if you have m R star m Y star and m B star, you can compare them with triangular carrier as shown here and the intersection of these m R star m Y star m B star with the triangular carrier, would give you the switching instance of the respective phases.

So, you can also produce the same PWM output from this so called triangle comparison approach and that is what we emphasize in terms of equivalent now.

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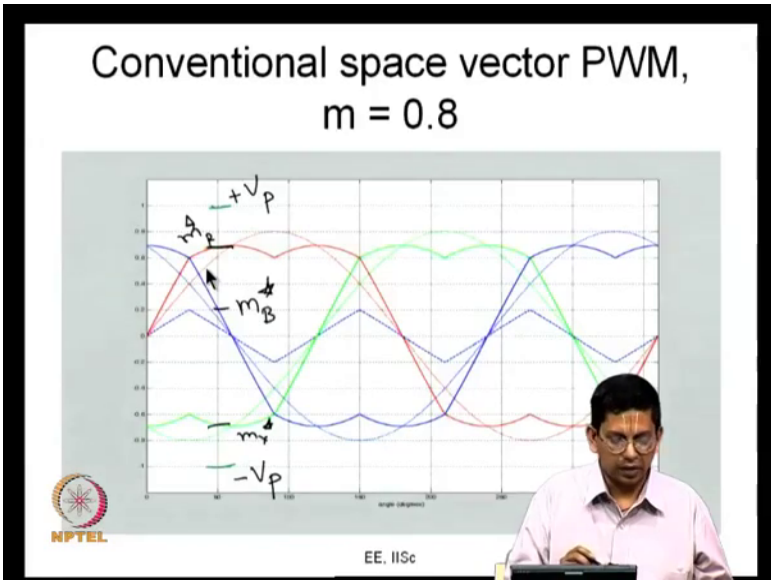

So, what needs to be done you have to produce the appropriate value of m R star, m Y star and m B star, that is how we saw that. Now this is your m R, if this is your m R what you do is you need to know what is your common mode component and the common mode component we is found was 50 percent of the middle value. For example, you take this region let us say 0 to 30 degree, B phase is the highest which you could call as a max, y phase this is B phase sign here and the R phase sign is the middle valued sign, you can call it a mid and the B phase are I mean the yellow phase which I am I have given in green color is the minimum most negative one and we can call this a minimum. So, you take a mid; a mid is this red phase take 50 percent of that that is what is shown by the blue one. And similarly between 30 and 90 degrees, red phase is a max and this m is that is the blue phase is lower than the red and it is higher than the yellow phase. So, this is what gives you your m mid this line. So, half of that is what is given by here.

So, this is half of m mid you that is a common mode signal, you add that common mode signal then your R phase sine wave which is like this becomes a modified waveform as shown like this. So, that is your R phase modulating, modified R (Refer Time: 10:39) that is your m R star. Similarly here is in m Y star here is an m B star you compare this with triangle of carrier to produce the space vector PWM, this is a very very efficient way of doing it. So, this is what we looked at and know this shows that they are equivalent now.

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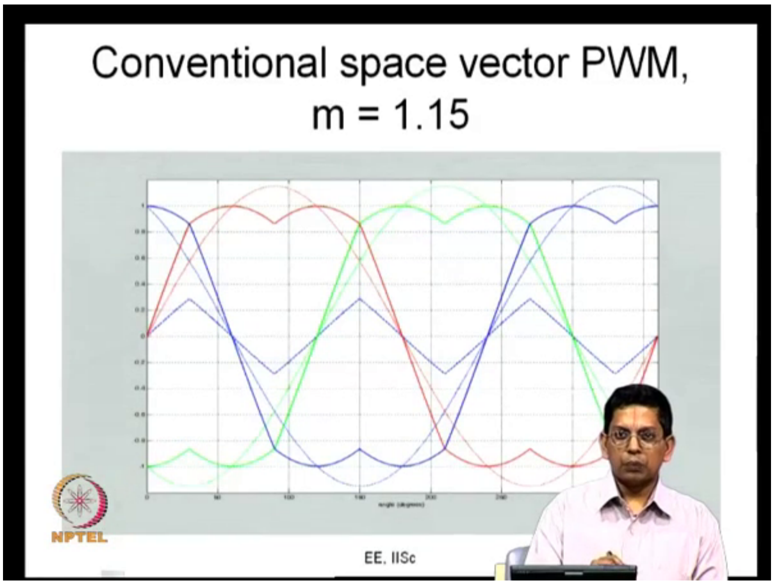

So, this is only to show that you can go a little higher than that, that the modulation you know this is one corresponds to the peak of the carrier do. You see that the signs the peak of the sine wave is 1.15 some 15 percent higher than the peak of the carrier, still what happens? When you add the common mode component, the effective value comes below and the peak value is just touching one.

So, the peak value of m R star not exceeding one, you can go and have a peak of up to 1.15 for m r. So, you are able to pack some 15 percent higher fundamental voltage, here just as we did in third harmonic injection with one sixth third harmonic injection. So, you do this now. So, this is a look at conventional space vector PWM from this space vector point of view, from the triangle comparison point of view.

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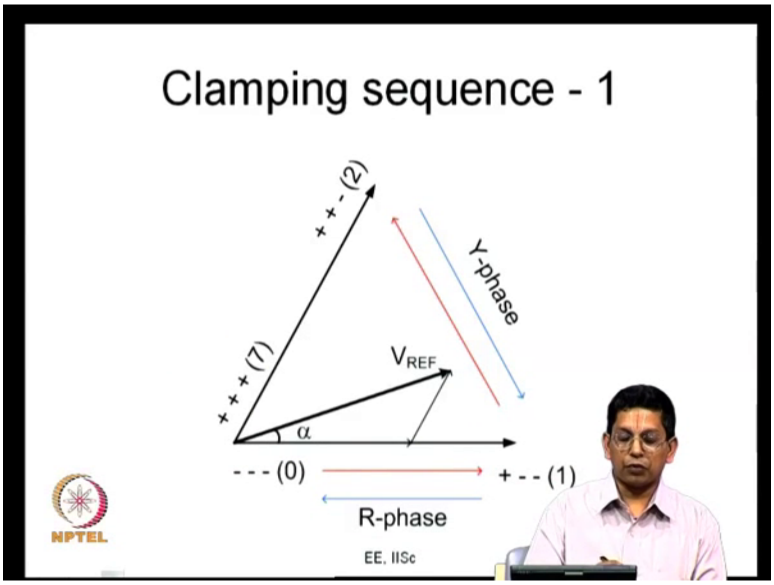

So, then the bus clamping what we did was, see this is a null vector the total null vector has to be applied for T z seconds in conventional PWM you apply this for T z by 2, we apply that for T z by 2. Somebody can ask a question why not apply only one zero state why not apply minus minus minus alone for the entire a T z. So, you can still produce same average voltage vector, you apply this for T z seconds then move here and stay here for and apply for T 1 seconds, and then after that you switch y phase and go here and apply this for T 2 seconds and the result is the same. This is the same, same average vector as what you would get; you know if you if you applied this for T z by 2 an if you applied that for T z by 2.

So, now what you do is you are you are saving one switching that is what you do. This has the effect of increasing the harmonic distortion that we will see a little later and you know at, but at the same average switching frequency you can also reduce the harmonic distortion using this, but those are discussions we will take up on the module on analysis of a current ripple. So, right now we will just look at the pulsewidth modulation generation of PWM wave forms, you see that there is one switching less you go 0 1 2 and the next sub cycle you can come 2 1 0. So, what happens because of this is the B phase you see it is always negative here; the B phase is getting clamped to the negative dc bus.

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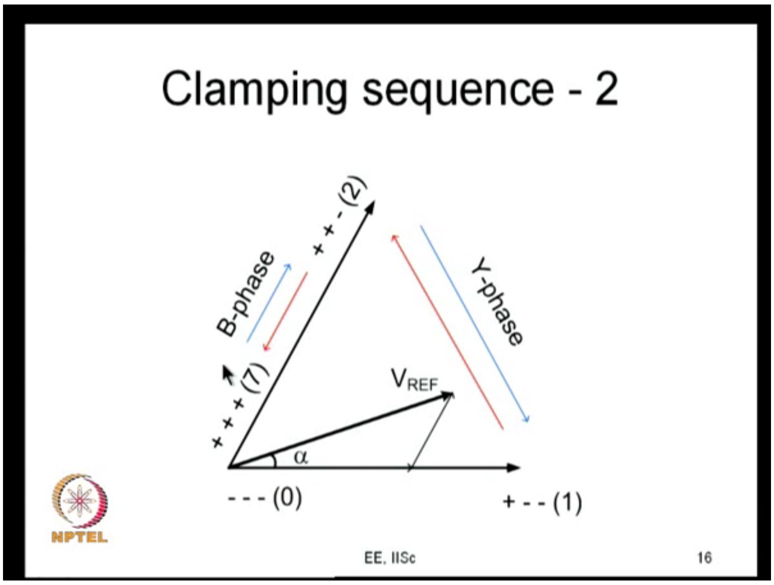

The same way you can skip the zero state minus minus minus totally, and apply only plus plus plus for the entire duration T z; so from plus plus plus you switch B phase you go to plus plus minus and you switch y phase and you go to plus minus minus. On the same way you can go back 1 2 7 7 2 1 1 2 7 7 2 1 and so on excuse me.

So, in this case what happens is, R phase is always connected to the positive here you see R is positive you are also you see R is positive you are also you see R is positive. So, R is always connected to the positive bus. So, this is R being positive. Now let us move to the other one.

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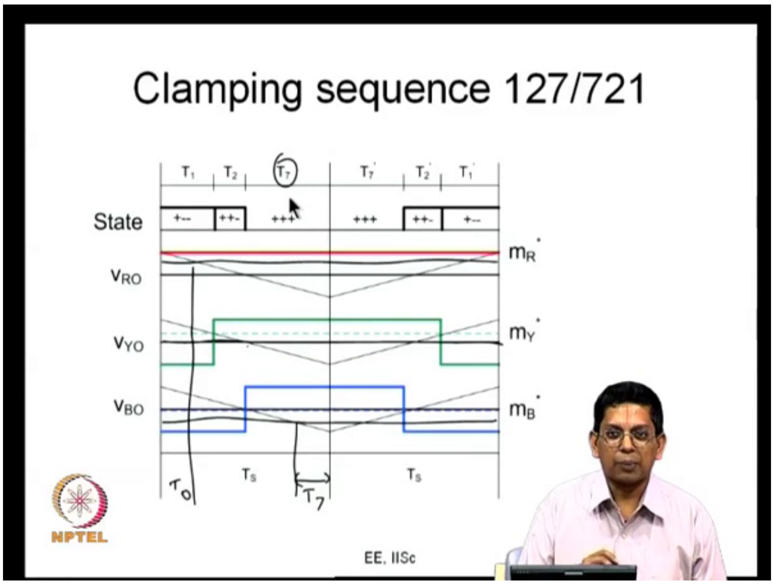

So, that is this is 1 to 7 or 7 to 1 seen in and the time versus time now. So, this is 1 and 2 this is plus minus minus plus plus minus and plus plus plus applied and hear you another your sequence, and R is clamped as you can see V R O is always equal to plus V DC by 2, and you take V Y0 it switches as we shown here and V B0 it switches like this now, and once again you look at it here there is V R O average. V R O average is equal to V DC by 2 here and the V Y0 average is shown by the dashed line and V B0 average is shown by this dashed line. M R star m Y star and m B star correspond to the average voltage is V R O average V Y0 average and V B0 average right.

So, you have this average, you are m R star m Y star and m B star you can compare them with triangular carriers now what you are doing? You can once again you will be able to generate the appropriate switching instance. So, to say that you can do the calculations either in the space vector domain or you can go and produce these waveforms from the triangle based on the triangle comparison approach. So, all that you are doing is you are effectively adding a common mode, what you are you are you are dividing the null vector time you had a 0 here you are entirely applying T z, it is just has the effect of adding the common mode here there is nothing more than that. So, we move here.

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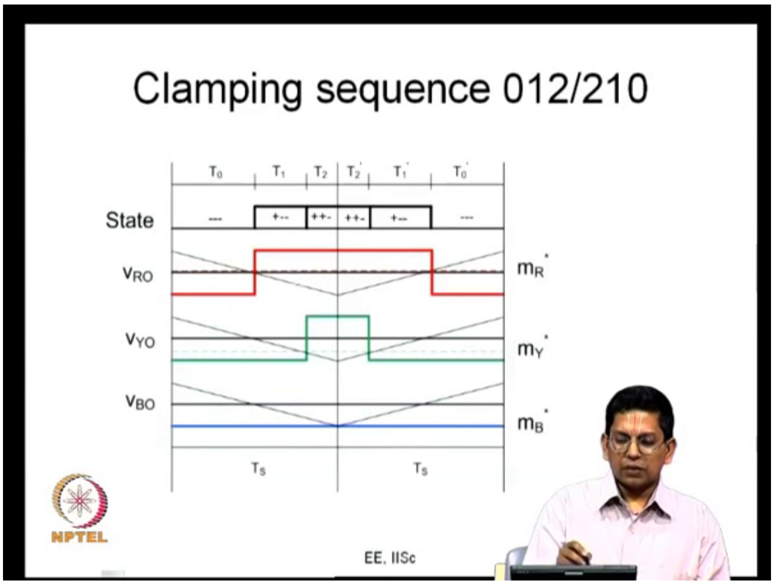

This is the same 0 1 2 1 2 and 0 here this is a case where the common mode is negative you can see that the same m R, m Y, m B results in a m R star, m Y star and m B star here such that m B star is equal to minus 1 or it is equal to the negative peak of the carrier m B star is equal to the negative peak of carrier, all the values have decreased from m R, m Y, m B some negative common mode component has been added here to come up here whereas, in the earlier case the common mode component added is positive so that you know m R which is the highest of the 3 is gone and is become equal to plus V DC by 2 R this is equal on to the v peak of the carrier.

So, here you have added a positive common mode component, such that your m max becomes equal to the v peak. Here you have add a negative common mode such that your m minimum is equal to minus v peak that is how you do now. As a result of this addition of common mode components, you end up applying only one zero state fully and are the other zero state fully now and this has the effect of clamping one of this now and this is a 60 degree clamp which we saw earlier.

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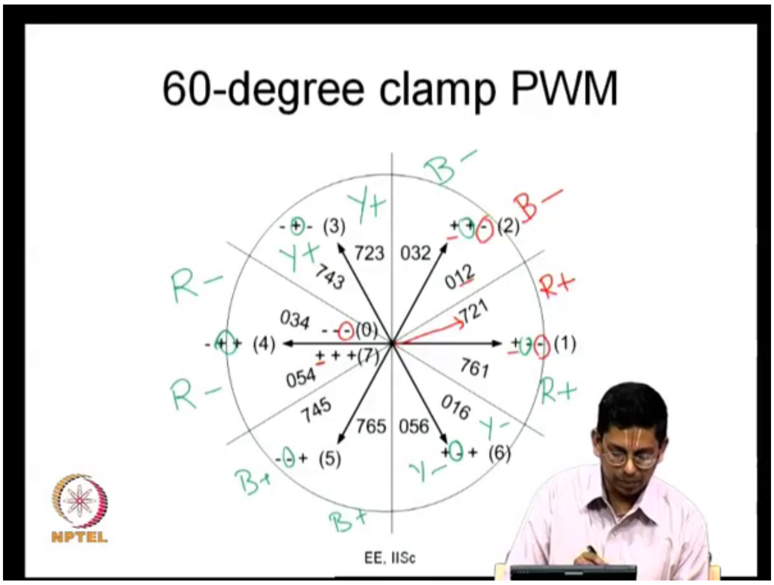

Now, we have to take a slightly you know careful look at this, because this is very very important for the advance bus clamping which we need to be doing now. So, as I said here when you use the zero state 7 to 1 let us look at that. So, 7 has R phase is positive, 2 and 1 you know all these cases you find that R phase is positive this is what we had seen earlier. So, what happens is in this region you have R clamp to the positive dc bus now.

So, in sector one you can either skip minus minus minus R plus plus plus, by skipping minus minus minus we have got R clamp to the positive bus, you take this 0 1 2 now. If you take 0 1 2 what happens? In 0 1as well as 2 you will find that this is 0 this is one this is 2. So, I have encircled all these 3; in all these 3 you find that the B phase is clamped to the negative bus and therefore, this leads to the clamping of B phase to the negative bus.

So, in sector 1 you have two options; either to use the zero state 0 throughout or the zero state seventh throughout, either use the zero state zero throughout or zero state seventh throughout if you want intelligent bus clamping. In either case Y phase has to switch why because you have active vector 1 and active vector 2. If you want to make a transition from active vector 1 to 2 or from 2 to 1 you have to switch y phase and both these active states have to be applied. You see it is plus minus minus and you see it is plus plus minus. And therefore, y phase always has to solution and it cannot be clamped.

What can be clamped? It either R phase or B phase can be clamped. If these null state that you use is plus plus plus and avoid this other zero state minus minus minus, then you have the result of R phase getting clamped to the positive bus. Again if you have a reference vector falling within sector one, and if you are if you are using minus minus minus and not using plus plus plus, you will have this of B getting clamped 2 a negative dc bus.

So, you can actually call in this sector there is some terminology y phase can be called as the unclampable phase, y phase cannot be clamped here why? Because for switching between the two active states, you need to switch y phase and you have to apply both the active states to produce an arbitrary reference vector. To produce any arbitrary reference vector let me just draw one vector here. If you need to produce any arbitrary vector as shown here, you need to apply excuse me; you need to apply active vector 1 active vector 2 on the null vector. When you have to apply both the active vectors you certainly have to switch y phase and you cannot avoid switching that, and you can call y phase as the unclampable phase in this sector it cannot be clamped.

Whereas, R and B phases are can be called as the clampable phases in this sector and R is particularly positive clampable phase, you can clampable a bit only to the positive phase you can clamp it to the negative phase and B can be called as the negative clampable phase. These things you can very clearly see only from these 4 inverter states and you know by avoiding one zero state you can see, what is the effect and that? You can also look at it from different perspectives.

Now, you look at it now, you look will let us try and correlate this reference vector let us say this is the reference vector now. There is some position it corresponds to, this position what does it correspond to. In terms of the fundamental angle if the reference vector is here, the reference vector has been rotating in the anti clockwise direction. So, what is happened is this? This vector 1 corresponds to the positive peak of R phase. So, this reference vector this position indicates a time a little after R phase positive peak. So, this is a region in the fundamental cycle, where your R phase is close to the positive peak how about the other phases.

Now you look at this is your R phase axis, where is your y phase axis? This is your y phase axis, you can call this as positive y phase axis and you can call this is negative y phase axis and therefore, this line this line is the zero crossing of y phase, this line corresponds to zero crossing a y phase. So, you can see that R phase is close to its positive peak and you can see that y phase is close to 0 what else? B phase and this is R phase axis, this is y phase axis and this is B phase axis and this is positive B phase axis and this is negative B phase axis.

So, this you can say you are in a region where the negative B phase is most negative it is close to its negative peak. So, that is what you get in this region. If you are in sector one, in you can then the reference vector is between active vector 1 and active vector 2, and if you look at it in terms of three-phase sinusoidal waves what you would see is, you would see that your R phase voltage is close to its positive peak and B phase voltage is close to its negative peak and the y phase is close to its positive 0 crossing. I am saying that this is positive zero crossing why? You can also see that you know this part is the positive half cycle and this part is the negative half cycle, you see it is plus minus minus here and from here it is plus plus here. Let me just choose some other color you can and point out that to you.

Now, let take a y phase and I am circling it with this is green ink now. You see that it is plus plus plus here and you can see that it is on minus minus minus here. So, this part this half cycle corresponds to negative half cycle of y phase and this half cycle corresponds to the positive half cycle of y phase. So, you just we need to be you know increasingly clear about the correlation between three-phase sine waves and the position on the reference vector, we need to be able to correlate these two very well now.

So, we call this as bus clamping PWM because you know every phase gets clamped to one bus. Now if you take here this is also R is connected to the positive dc bus here also, and the same way and we looked at a as we looked at yesterday if you here also; here you will find R phases once again clamped, R phase is clamped to the negative bus here also you will find R phase is clamped to the negative bus how is that excuse me. So, 0 3 4 or 0 5 4, when you is 0 it is minus minus minus you go to 3 it is minus plus minus and 4 is minus plus plus. So, you see that R is negative then both the active states are applied and the 0 state applied is 0.

Similarly, 0 5 4 in 5 as well as 4, R phase is negative and this is 0. So, minus minus minus, this is what you have. So, what else you have? This is R minus and R minus, this is R plus and R plus. So, this corresponds to the middle 60 degree duration of the positive half cycle of R phase, now this line corresponds to the positive zero crossing of

R phase, this is the positive peak of R phase, this is the negative peak of R phase, this is the positive zero crossing of R and this is the positive peak of R phase which we can call as 90 degrees.

Now right and this line corresponds to 60 degrees and this one corresponds 120 degree. Between 60 and 120 degrees, you have R phase clamped that is R phase is clamped during the middle 60 degree duration now if its positive half cycle where it is clamped to the positive dc rail, and you take the other corresponding 60 degree duration in the negative half cycle this is the middle 60 degree duration in the negative half cycle and you see that R phase is clamped to the negative bus and these seats R minus and R minus here is that fine.

So, the same way you will see that everywhere every phase will be clamped around, its peak value excuse me let us just do it for one more phase so that it becomes clear in right. So, you have R and R you take it you should look at y let us say you look at 7 2 3, what is 7 2 3 plus plus plus and 2 is plus plus minus and 3 is minus plus minus. So, y is connected to the positive is clamped to positive phase here and a 7 4 3, 7 is plus plus plus and 4 is minus plus plus and 3 is also minus plus minus, therefore here also y is connected clamped to the positive bus here. The same way you will find that y is clamped to negative bus in these two regions and you will have B clamped to negative bus and here you will have B clamped to positive bus.

You will find that everywhere it is in the middle 60 degree duration of its positive of sign, if you take y phase this is the zero crossing of y phase and this is the positive peak of y phase and this is the middle 60 degree duration in the positive half cycle of y phase it is clamped here and that is the reason you there is this screen called 60 degree clamp PWM. It is just a name after all when sometimes it is called d PWM one in some literature, we call it 60 degree clamp because it is clamped you know when whenever a phase clamp during the middle 60 degree duration is half cycle.

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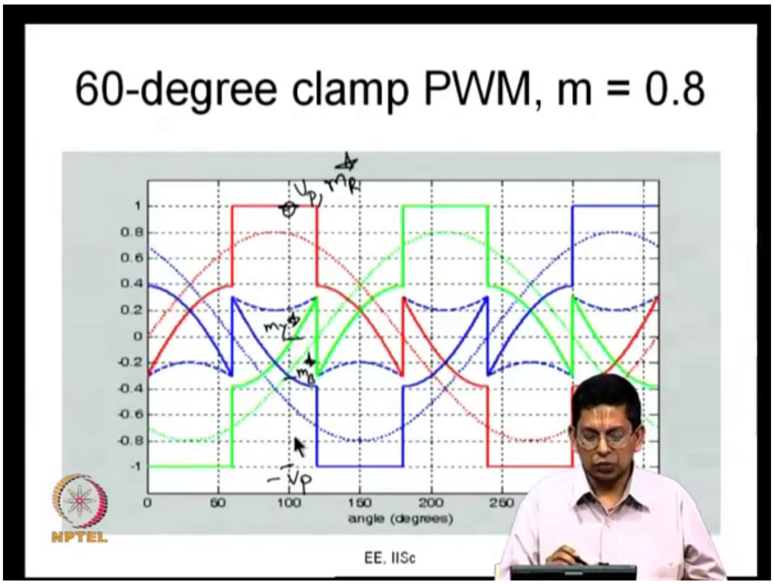

In a in every half cycle we could call it as 60 degree clamp PWM and this is the modulating these are the modulating signals as we saw before.

Now, what do you if you if you compare this with the triangular carrier, you can observe that phase is clamped here. So, it does not switch at all here whereas, a phase would switch here for example, at the carrier frequency it will switch at the carrier frequency. So, what will happen is, here it switches at the carrier frequency here it switches at the carrier frequency whereas, here it is clamped. So, you can define as what is called as average switching frequency. So, the switching frequency here is fc, here as fc, here it is 0. So, the average switching frequency will be two-thirds of fc that would be the average switching frequency over a line cycle.

So, you are able to save about one third of the cycle that is what you know that is one advantage of bus clamping PWM. You are able to reduce the number of switching cycles and if you are able to reduce the number of switching cycles you are also able to reduce the number switching losses now. So, I am doing this because you know we just have to get into the advanced bus clamping now.

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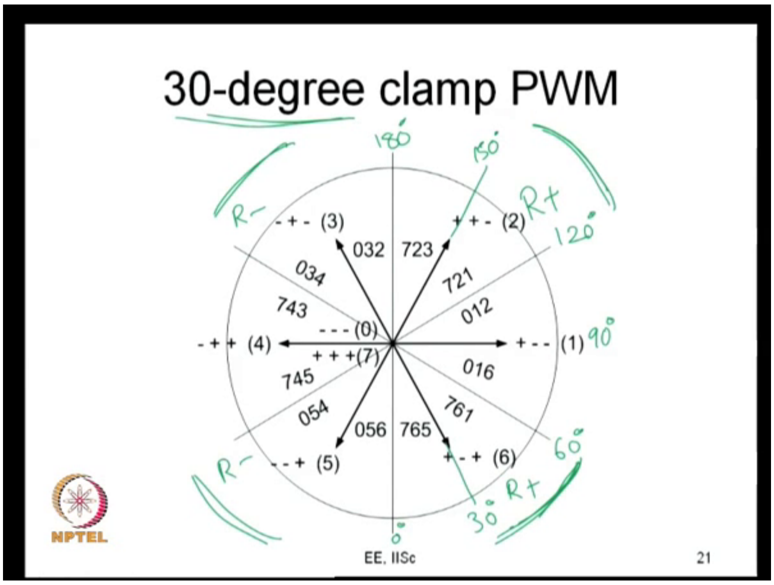

So, this is again you have your 30 degree bus clamping and in this 30 degree bus clamping if you just let us focus just on the R phase alone, you will see that R phase is clamped to the positive bus here and R phase is clamped to the negative bus here. Again you will find that R phase is clamped to the negative I mean positive here negative and here also R phase would be clamped to the negative bus here.

And if you call this, this is what is 30 degrees, this would correspond to 60 degrees. If you start your cycle at 0 degree this is 0 there is R phase zero crossing 30, 60, this is 90, this is 120, this is 150, this is 180 and you can see that R phase is clamped between 120 and 150 and it is also clamped between 30 and 60. You see 0 to 90 is one quarter and 30 to 60 is the middle 30 degree duration in a particular quarter. Here again you see it is in the middle 30 degree duration in another quarter, here also you will find that it is clamped to the middle 30 degree duration in this quarters and hence we call this as 30 degree clamp PWM.

So, in this what you will find is not only R phase you take any phase Y R B also, every phase you would find that is clamped to its dc bus during the middle 30 degree duration in every quarter cycle right and it is clamped at the positive bus, if it is positive half cycle it is to the negative bus if it is a negative half cycle and this is what is the corresponding modulating signal that we had seen here.

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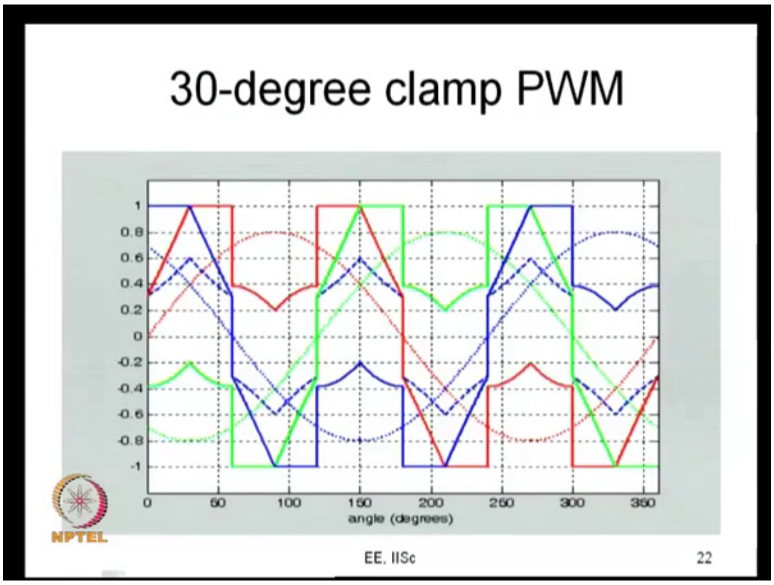

So, here again the a switching frequency is 0, here again the switching frequency is 0 here it would switch at carrier frequency. So, once again you know what you will have is for 60 degrees it is not switching, 30 degree here and 30 degree here and your average switching frequency will be 2 by 3 times fc, you are fc is here carrier frequency right.

So, we have got advanced bus clamping PWM, where you will not just have these 2 cases that is switching at carrier frequency and switching at 0, you will also have a situation where this switch are double the carrier frequency.

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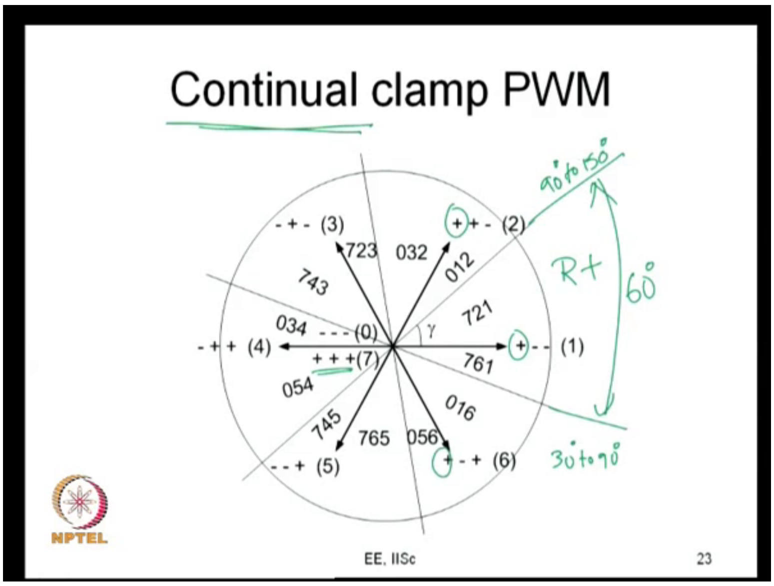

So, this is again continual clamp which should we do this, continual clamp is a generalization of 60 degree clamp. So, you have 7 to 1 you have 0 1 2, in the case of 60 degree clamp what we found was the changeover from of zero state occurred at the middle of the sector that is what is gamma is equal to 30 degree. Now you do not it does not have to be at gamma is equal to 30 it can be at any arbitrary gamma gamma can vary anywhere between 0 and 60 degree and that is what you would call as continual clamp why do we call this continual clamp as I mentioned the other day.

So, here you find that R phase is clamped here, you find R phase is clamped continuously to the positive dc bus because active state 7 is used, all these states 1 2 and 6 if you see here R is positive here also R is positive here also it is positive. So, in all these active states R is positive and you are using only plus plus plus and you are not using minus minus minus, because of that R phase is getting clamped to the positive bus when minus minus minus is not used and you see that R phase is clamped over this thing now. This is a 60 degree duration now. So, it is continuously clamped for a 60 degree duration and therefore, you call this continual clamp PWM.

So, this is not exactly between 60 to 120 degree. So, this can be anywhere, this can be anywhere this can actually start from 30 to 90 degrees and this could be anywhere between 90 to 150 degrees.

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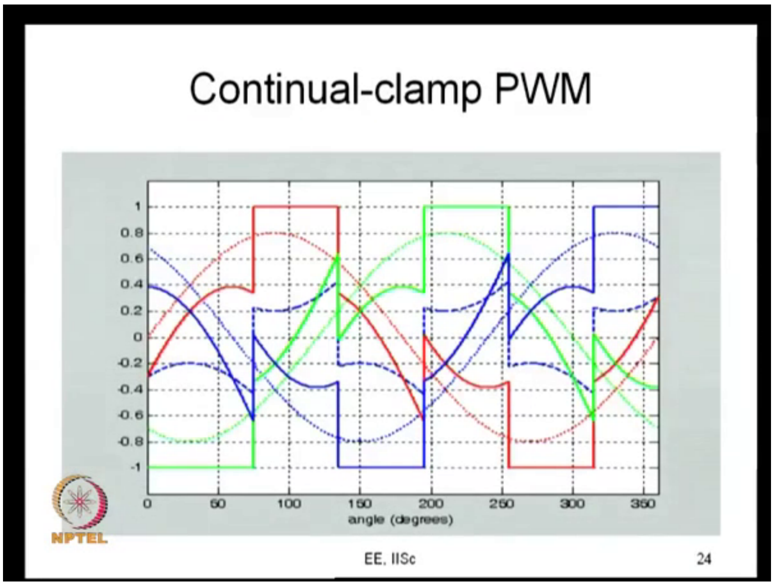

So, that is what is shown here in this waveform, you can see that it is clamped it is it shows for some particular value of gamma if the value of gamma is equal to 60 degree it will come to 90 to 150 degree and otherwise it is if gamma is 0 it could be 30 to 90, if gamma is equal to 30 it will be exactly 60 to 120 as in the case of 60 degree clamp now.

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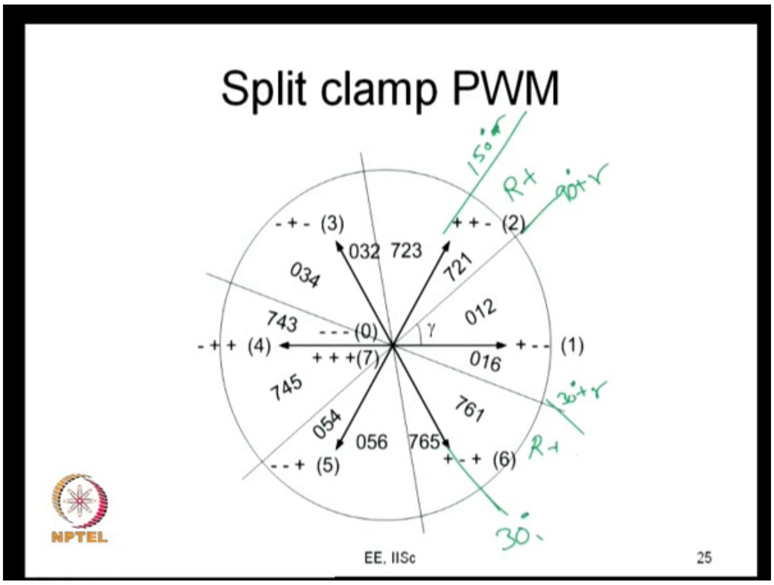

So, we go to a split clamp which is again a generalization of what we saw before that is 30 degree clamp. So, this is you have R phase clamp to the positive bus here also you have R phase clamp to the positive bus. So, this is 30 degrees sorry this is 30 degrees and now this is 30 plus gamma, this is 150 degree sorry this is 90 plus gamma. So, here it is gamma. So, what you have is, this duration is gamma and this duration is 60 minus gamma. So, it is clamped for duration gamma in one quarter cycle and it is clamped for a duration 60 minus gamma in the next quarter cycle. So, it is split clamp a particular cases when gamma is equal to 30 and that is what is called as your 30 degree clamp.

So, this split clamp PWM has not been realized, I am a has not been investigated much in the literature, but I would say that this split clamp PWM has better harmonic distortion than this continual clamp PWM. I am just making an assertion here will prove this when we look at you know this they look at the analysis of line current ripple.

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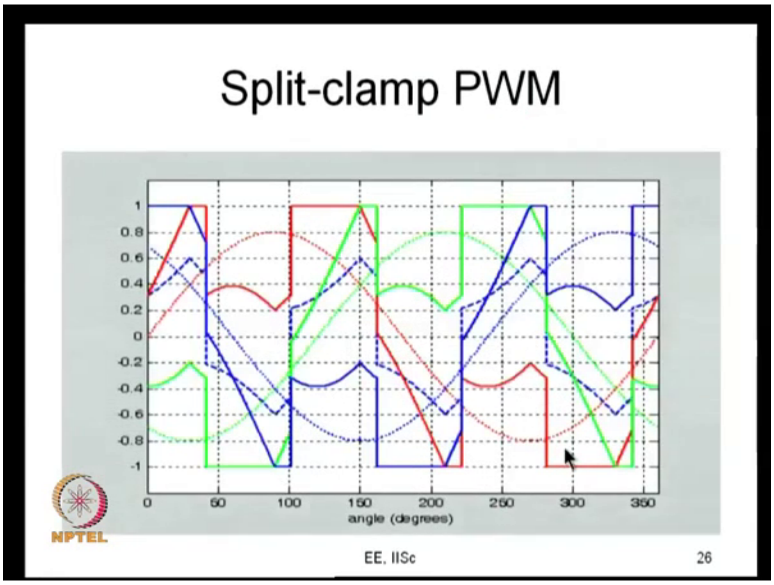

So, right now let us just take it that it is going to be better than that all right then. So, this is how the split clamping PWM signals are going to look like.

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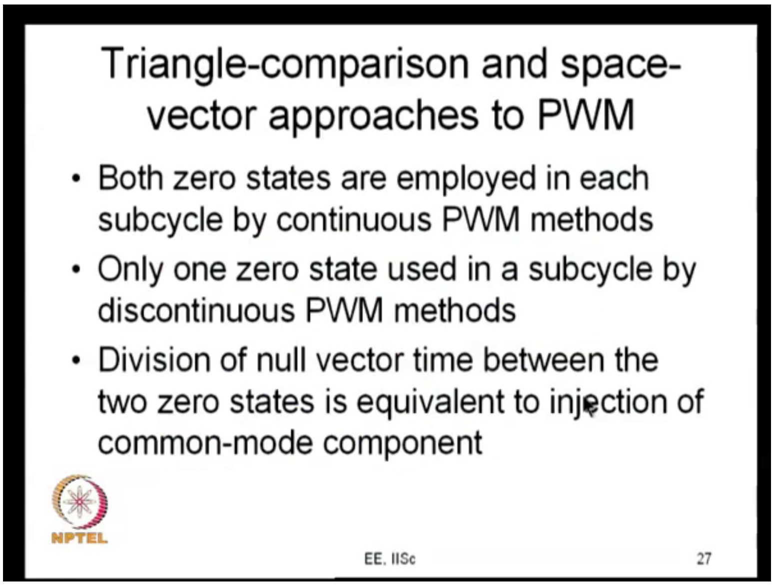

Now, let us just take a look at that we have been looking at going through both triangle comparison and space vector approaches, we looked at conventional space vector PWM we looking at bus clamping PWM, but in all these cases what we have been looking at as you know we are not only looking at from the space vector point of view you have been looking at it from the triangle comparison point of view also.

Now, let us just make a few points here before we proceed to the advanced bus clamping once here. You see that both the 0 states are employed in each sub cycle by continuous PWM method. Now conventional space vector PWM is a continuous PWM method. Now this is a continuous PWM method why would you call it as a continuous PWM? You see that the modulation signal is a continuous function of time not only this, you can add sign and to sign you can add any third harmonic instead of this you can also add a third harmonic you can add anything, any common mode which is a continuous function of time. The sine wave itself is a continuous function of time and to that if you add a common mode component which is also a continuous function of time, the resulting modulating signals such as this are also continuous times now if it is continuous. So, what?

Now, let us take it its continuous and it is a linear modulation, you take this now let us say this is this angle is 60 degrees though you cannot read that very clearly, you can see that this is 60 degrees let us consider a carrier cycle at 60 degree. Now what happens now? You look at what is your R phase? This is your R phase modulating signal this is a m R star and what is your y phase modulating signal? This is my star and what is your B phase modulating signal? This is m B star. So, you see that you have when where is your carrier peak the carrier peak is here, do you want me to draw let me just draw that. So, the carrier peak is here, the carrier peak is here this is the positive carrier peak this is the negative carrier peak right let me choose red ink and show where you have the red one.

So, if you look at the red phase the red phase is here or maybe I will just choose a black color or so, so that everywhere you can get. So, this is your red this is your yellow phase this is your blue phase; just to avoid confusions I will make this further clearer this is plus V p this is minus V p and what is this? This is m R star, this is m R star and what is this? This is m B star and this is m Y star. So, you see that between V p and m R star there is some gap.

So, there is during this interval is when one zero state is applied. So, during all you know in during this small interval what you will find this the carrier will be greater than m R star m B star as well as the m Y star, the carries is going all the way from V p to minus V p. If you draw the carrier on this it will almost look like a straight line, there is a small slope it will almost look like a straight line. So, I am not drawing the carrier really speaking. So, it is going to be like this.

So, initially all the phases are go if you consider the carrier dropping from plus So, right now. To minus V p initially you will find all you know the 3 signals the carrier is greater than all the 3 signals m R star m Y star and m B star therefore, you will have zero state up right now. Here you will find R phase alone switches and so between these two, you will have R is positive plus minus minus is what you will get here and this m B star after the m B phase will also switch, you will get plus minus plus in this a interval and after that you will get plus plus plus.

So, what you see is a one active state here and another active state here. When you start it is one zero state which is minus minus minus, when you end it is another zero state plus plus plus. So, this is because there is any continuous modulating signal. Now on the other hand if you do not have a continuous modulating signal you go to a discontinuous modulating signal like this and you consider a particular instant as shown here let us say I consider the instant 100 degrees, you consider this instant 100 degrees and here this is equal to your V p, this is also equal to your m R star.

So, even as you start your R phase is always positive R phase is never negative, here if you look at this. So, this is m R star and where is your m Y star and m B star if you look at here you will take this. So, this is m Y star and this is m B star and this is minus v peak. So, what you get here is you get your V p and m R star are equal. So, one zero state is never applied. So, you know R phase is always positive and towards the end there is a zero state applied. In this case when you are between that when you when your carrier is falling and the carrier is below m B star, you will get you know the carrier is lower than all the 3 values m R star m Y star and m B star. Therefore, all the positive device will be on you will have plus plus plus, but minus minus minus is never applied.

So, whenever you or do not have discontinued whenever you have the 3 signals m R star m Y star and m B star within minus V p and plus V p, not touching not equal to that. So, like the m max whatever is the maximum modulating signal is lower than plus V p and the minimum modulating signal is greater than minus V p you will have this thing. So, whenever you have this continuous modulation, whenever you have a continuous PWM and it does not exceed.

So, the 3 modulating signals are there m max m made and m min none of them exit plus V p or minus V p; m max is lower than plus V p and m min is greater than minus V p under that condition you will see that both the 0 states are applied. Now this happens in its context conventional space vector PWM. Only thing it the both the 0 states are applied for equal durations this happens in sine triangle PWM, but both the 0 states are not necessarily equal and you had third harmonic you both 0 states are applied you consider a third harmonic injection with k equals one by 4 then you get a situation where both the 0 states are applied more or less for equal durations of time, ok.

So, on the other hand if you look at the bus clamping PWM method the discontinuance PWM method, you will find that there is only one zero state used in a sub cycle. So, what you really see here is it is division of null vector time between the two zero states, this is what changes deviation of null vector time between two zero states now. How long you are applying 0 how long you are playing and that is equivalent to whatever common mode is being injected. So, we have some common mode that is being injected. So, in all the cases now there are certain common mode has injected here, that is a positive common mode now on this it cell let me just draw and give some indication let us say that common mode is different.

Let me say the common mode is different. So, all of them are a little lower than that, the signal is a little lower and again this average voltage is also little lower and this average voltage is also little lower. All the 3 average voltages are all the 3 m R star m Y star and m B star I have added some delta m negative delta m through all of them. So, I have they have all reduced because of this what happens if you finally, look at it this is your 0 vector time, this has come down what was originally your 0 vector time this is T 7 entirely T 7 now this is what is your T 7, this is what is your T 7 and T 1 and T 2 are unchanged T 1 and T 2 are unchanged why because if you look at this, this has come down and therefore, the switching instant has shifted.

So, now this switching instant is also shifted. Therefore, effectively the duration for which T 1 is applied is unchanged excuse me. For T 1 is applied is unchanged and again the duration for which T 2 is applied is unchanged with the duration for which T 7 applied is changed now. So, what happens because of that? Anyway what you will see that there is T 0 here, this is T 0 this is the duration for which T 0 gets applied and T 0 plus T 7 is equal to this original Ts T z.

So, what happens is when you add a common mode component simply division between T 0 and T 7 this changes, original sine waves m R m R m Y m B and from there you have added m R star m Y star m B star, and the particular case we considered was where the positive common mode component was conceded you know is added and m R star becomes equal to plus V p. So, what has happened is entirely only the zero state 7 gets supplied for the entire duration T z and minus minus minus never gets applied.

On the other hand, I have shown for another example what I would run here is, some other value of common mode. If it is some other value of common mode what you see is you get both 0 and 7 are getting applied , but the sum of T 0 plus T 7 is equal to the old T z that is what happens now. Therefore, you get that is to the point that I was making the null vector time is what is different, the division of null vector time between the 2 0 states that is equivalent to injection of common mode component when you add common mode component what effects exactly happens is the active vector times do not change, but the time for which the two zero states are applied changes, but the total null vector time is still the same now.

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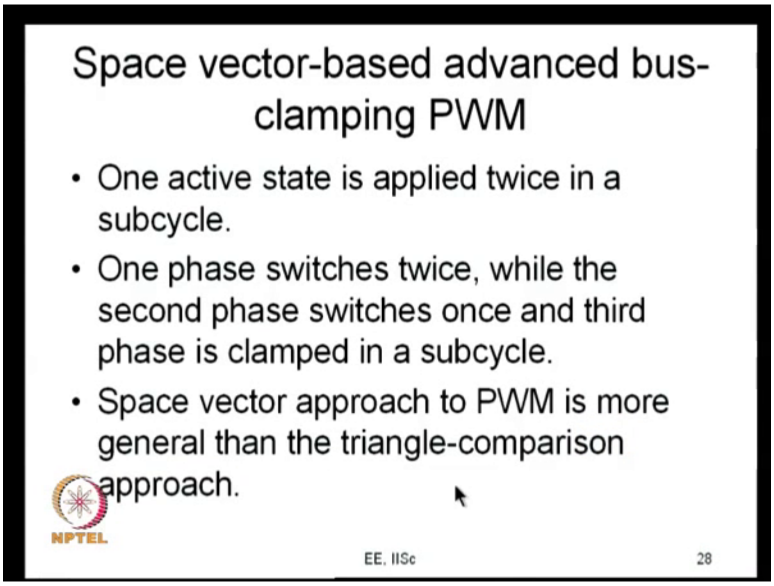

This is about triangle comparison in space later approaches and we just go down and to see space vector based advanced bus clamping PWM, here also you what you have is one active state is applied twice in a sub cycle that is the important difference. In the previous cases all the previous cases you have an active state getting up red only once in a sub cycle, you have active state 1 and then active state 2 here what you can think of as active state 1 2 and back to active state 1.

You have a situation where one phase which is twice well the second phase which is once on the third phase is clamped, in bus clamping you will have this situation where one phase which is once in a half carrier cycle and the other phase is clamped I mean 2 phases will switch like this and one phase is clamped yet in advanced bus clamping you have one phase switching twice and the second phase which is once while the third phase clamp this is this a difference now.

And now we are going to say space effective approach is more general than the triangle comparison approach which is what we are going to bring out now.

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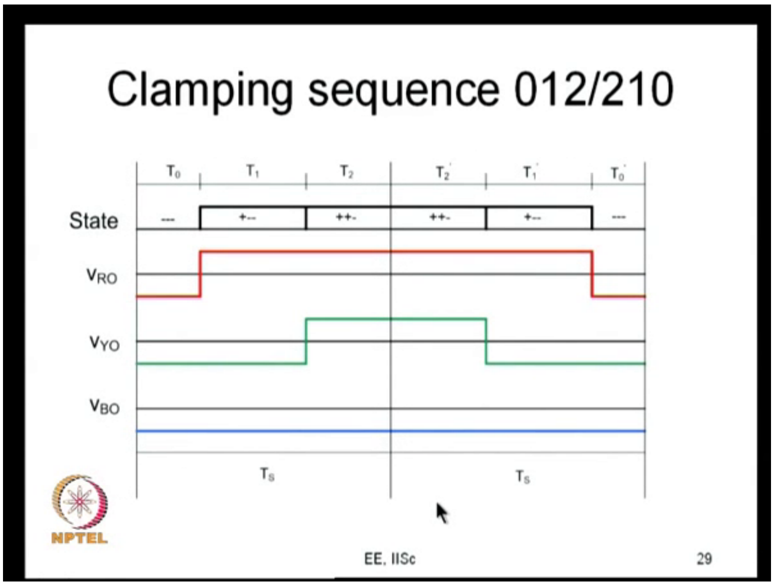

So, this is your clamping sequence, just start with that clamping sequence where you are applying 0 1 2 minus minus minus plus minus minus and plus plus plus this is going like this. So, you have V R O switching like this and this is V Y0 and this is V B0 which is always equal to minus V DC by 2. So, now, this is 0 1 2, 1 and 1 2 and 0.

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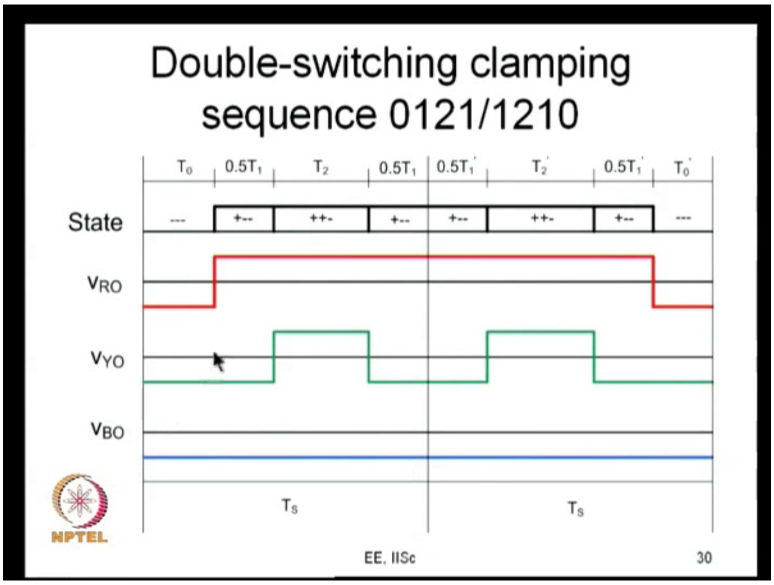

Now, if you look at this 0 one 2 and whereas, here it is 0 1 2 1. What am I doing I am applying 0 for T 0 seconds then I am applying one not for T 1 seconds, but for 0.5 T 1 seconds. Then I am applying T 2 mean active vector 242 seconds as before, then I am going back to state 1 and applying this one 0.5 T 1 seconds. So, this is a null vector is applied through only one zero state minus minus minus and T z. So, if will take active vector 2 that is applied for T 2 seconds as determined by calculations, we have an expression you know T 2 is V REF sine alpha by VDC sine 60 multiplied by T etcetera. Similarly you have T 1 some required T 1 that T 1 we are not applying you know the active we are applying active state 1 twice we are going from 0 to 1 2 and back to one right.

So, what happens to you? Now you see that R phase switches like this whereas, y phase switches twice when you are going from 1 to 2 and 2 to 1 y switches twice like this. This is a difference that I was saying now which happens in. So, and one of the phase is clamped now, because you are using only one zero state plus plus plus is never used you see that B phase is always negative. And therefore, you call it a clamping sequence because B phase you can see it is clamped here it is always equal to minus V DC by 2 in this case whereas, y phase switches twice and therefore, you can call this double switching clamping sequence. In this particular example your B phase is clamped to the negative bus and Y phase is switching twice and 0 1 2 1 if is what you use in one sub cycle, 1 2 1 0 is what you can use in the next sub cycle.

So, here again whatever is your T 1 dash you are applying active state 1 for 0.5, T 1 dash and then 0.5 T 1 dash later, right.

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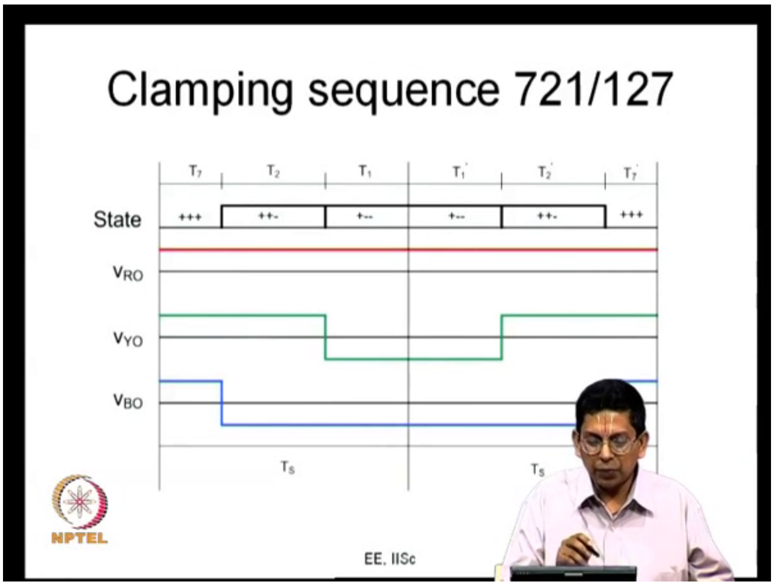

The same way if you start with the clamping sequence 7 to 1, 1 to 7 this is 7 to1, 1 to 7 and R phase is always clamped positive and y and B switch once each and every half carrier cycle.

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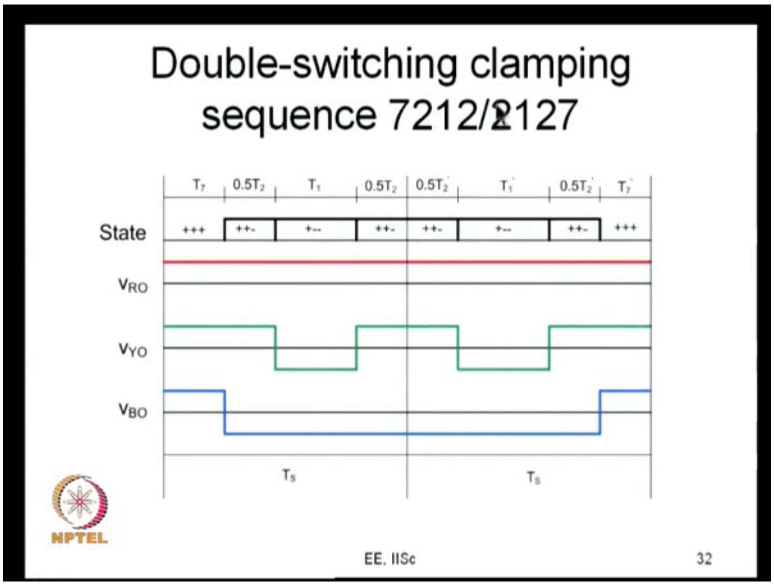

Now, you go here this is double switching sequence 7 2 1 2 this is not 7 2 1 this is 7 2 1 2, you apply 7 for a duration T 7 is equal to T z, then you apply T you apply active vector

2 plus plus minus you do not apply this for the entire duration T 2, you applied only for point 5 T 2. So, a from point 5 T 2 what you do? You go to active vector 1 and applied for T 1 seconds then from there what do you do? You go on apply active vector 2 for point 5 T 2 this is what you do.

So, active vector 2 gets applied twice, because why what happens because of this you have you see the 2 phases if you look at it in terms of phase, you see that y phase which is twice. So, there is an B phase which is just once now. So, you look at it here B phase which is once y phase which is twice R phase is clamped therefore, because R phase is clamped to the positive bus you can call this as clamping sequence and y phase which is twice you can call it double switching clamping sequence and what can be clamped it can either be R phase or B phase in sector one y phase cannot be clamped and in this case y phases double switched now.

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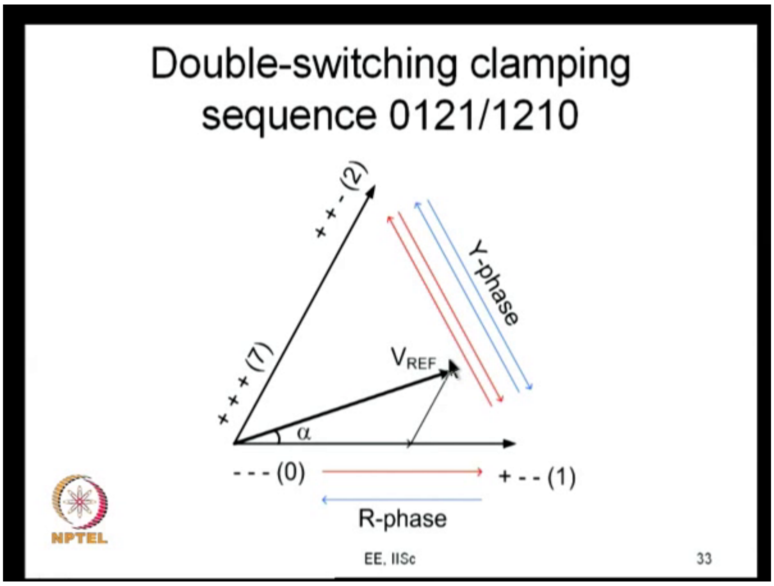

You can similarly think of other example; see here I have just shown this in a different on the space vector plane for an easier understanding. So, what do you do here? Let us say you start from 0 minus minus minus and then you go here you switch your R phase that takes you to plus minus minus. So, instead of staying here for T 1 seconds, you stay here only for 0.5 T 1 seconds, from here you switch switch which phase y phase then go to 2.

So, you are an active vector 2, you apply active vector 2 for T 2 seconds and from here a switch back your y phase and you return back to active vector 1 and stay here for T 1 by

2 seconds. So, Tz seconds here T 1 by 2 seconds here T 2 seconds here and T 1 by 2 seconds here. So, you end up getting the same average vector know, because you have applied the null vector for a certain time and T 1 is not applied continuously active vector 1 is applied for T 1 by 2 seconds now and T 1 by 2 seconds later and you still have this this fraction is still T 1 upon T s times V1 vector and vector 2 is applied for T 2 seconds. So, this fraction is vector 2 multiplied by T 2 upon Ts and what you get is the same reference vector this is the same reference vector you generate you know with the conventional sequence where you apply both the 0 states for equal durations of time and you know if you skip one of the 0 states through bus clamping you can produce the same thing and now using double switching clamping sequences you are able to produce this now right.

Now, you know we have moved off we have we are now not looking at the inverter has 3 different phases, you know are 3 independent phases we are looking at the inverter state and that is why we are able to say. The question is we are we are asking question why should I apply this active state continuously for T 1 seconds why not I apply it later why not I applied it for one once more. So, that is the answer to that now because from this phase vector domain you know that you have to apply the active vector 141 seconds and active vector 242 seconds and the null vector totally for these are seconds. So, it does not matter in what sequence you apply. You have to move in a particular sequence so that you do not switch unnecessarily, you see that every transition you are switching only one phase and you are still changing from one state to another here only R switches here only y switches therefore, every state transition there is only one phase switches other than that we are not doing anything.

So, now you are totally 3 switchings, we are avoiding B phase switching and we are switching y phase twice you may ask what is the advantage? Firstly, I am telling you it is possible to do this now and we will come to advantages a little later. One of the advantage is at high modulation indices, these kind of switching sequences can give you a lower harmonic distortion which we will address in the next module. And it is also advantageous for to reduce the switching losses under certain circumstances and particularly at high power factor this kind of switching sequences are helpful. Again, I will talk to you on that later when in the model on switching loss right.

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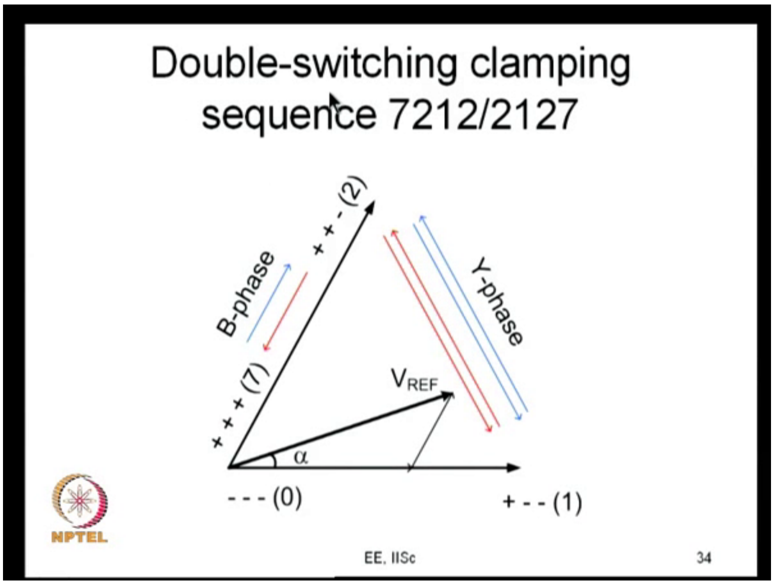

So, this is about 7212 here instead of using 0 I am using 7 and from 7 I go to 2 a stay here for T 2 by 2 seconds, I switch y phase and go one and apply active vector 1 stay here for T 1 seconds and switch back and come here and apply this for the remaining T 2 seconds.

So, overall I am applying active vector 1 for T 1 seconds and active vector for T 2 seconds and the null vector for T z seconds. So, I will get the desired average voltage vector. So, that is what we are doing you can apply the vectors in different sequences, but this act null vector is totally applied for Tz seconds, this is totally applied for T 1 seconds and T this is totally a plate for T 2 seconds is required and therefore, this produces the same average vector. So, what we are trying to say repeatedly is the same average vector can be produced by applying the voltage vectors in different sequences. So, there are different sequences are possible is the bottom line that we have been trying to emphasize now.

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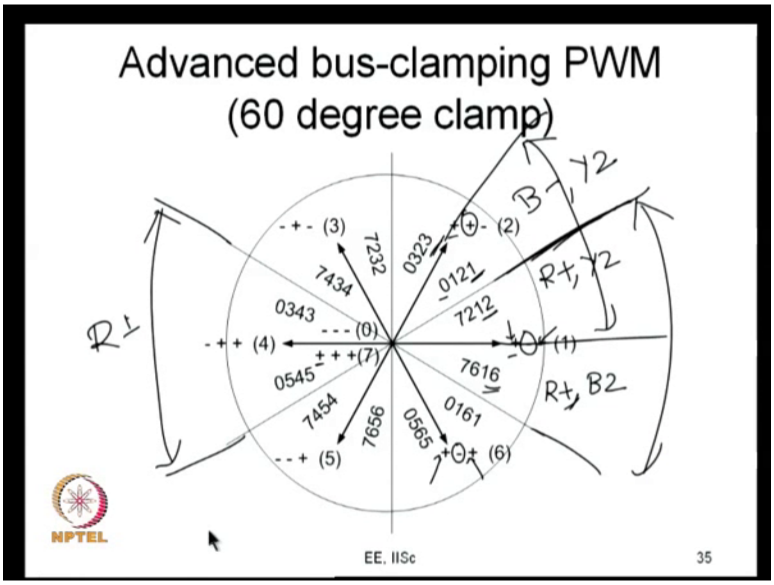

If you can see this, this is very very similar to our 60 degree clamp. This is 60 degree clamp I have just changed what is the change I have done here? Very very easy to see you see I have set 7 2 1 2 here instead of 7 21, instead of 0 1 2 I have set 0 121 you see this I have just changed the switching sequence nothing more I have done that is the reason I was emphasizing on bus clamping PWM so far because you know it is very important for us to go to this advanced bus clamping PWM. Sequence 7 2 1 and 0 and 2 I have replaced by 7 2 1 2 1 0 1 2 as shown here what happens because of that here because we are not using minus minus minus at all R is clamped to the positive bus, you can see that it is positive R is positive here at both the active states and your using only zero state 7 where again R is positive side as R is positive now.

Other than that what happens between 2 and 1 this is 2 and 1. So, what happens is y phase switches y phase switches; R plus and I am writing it as y 2 the notation here is y phase switches twice here what do I do? Here also I will see that R switches R is positive then how about y phase you can see that y phases this is6 and 1. So, here this is 6 this is 1. So, 6 and 1 y is like this if you look at the other side this is R 6 and 1 and what switches is B, this is B is minus and this is plus minus minus here, here you see that B is switching twice.

So, here you find that B is switches twice now. Let us go back to our sector one, in sector one what happens when you zero state 0 it is clamped or like B negative, this is very similar to the 60 degree clamp before now which phase switches twice? Y phase switches twice and this is the zero crossing of y phase. So, what you can see is R phase is clamped where is R phase clamped? R phase is clamped during the middle 60 degree duration, here also you will find that R phases will be clamped doing the middle 60 degree duration to the positive bus.

And now what do you say y phase now y phase double switches here this is y phase double switches here y phrase is double switching around the zero crossing this line is the zero crossing of y phase, this line is the zero crossing of y phase now. So, this is a particular advanced bus clamping PWM which is an extension of 0 degree clamp PWM, I replaced the sequences by the double advanced bus clamping sequences what it results in exactly is you know clamp on during the middle 60 degree duration as I showed before, in addition to that y phase or any phases double switching for a 60 degree duration around the zero crossing.

So, now you have a situation where let us call you know are for 60 degree centered around the zero crossing a phase double switches and 60 degree centered around the peak it is clamped and the remaining times the phase switches at the nominal switching frequency. So, the phase overall has an equal average switching frequency, what happens is there is a kind of redistribution of switching frequency that happens. It switches more often around the 0 crossings and it switches less often around the peak values of these voltages in this case now. With the average switching frequency is still the same as in the case of conventional space vector PWM.

So, this is from advanced bus clamping the PWM, I am coming to 60 degree clamp now.

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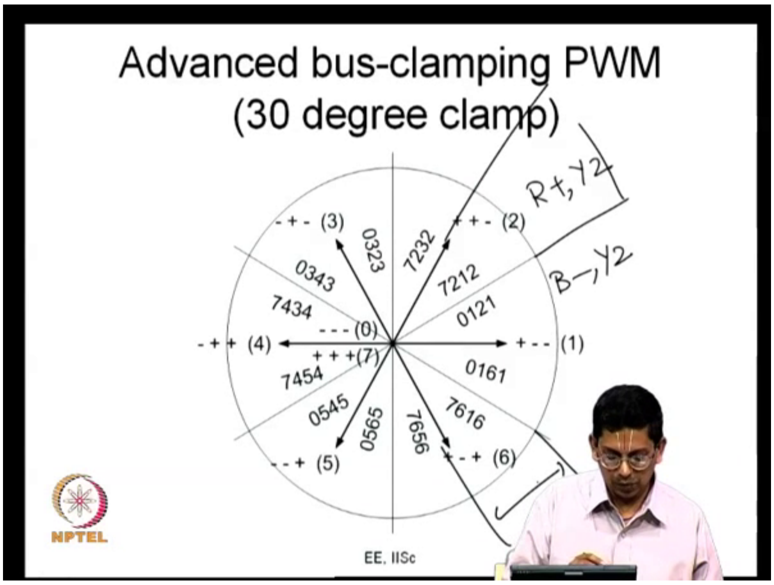

The same way I can do this I mean 30 degree clamp I am converted into advanced bus clamping PWM you can see the sequence instead of 0 1 2, I have written 0 1 2 1 instead of 7 to 1 I have written 7212 and I have made similar changes in all the other sectors nothing else I have done now. Now because of this what is going to happen? Here it is R is positive and here B is negative as before. In sector 1 R can get clamped to the positive bus if plus plus plus alone is used and B gets clamped to minus negative bus if minus minus minus alone is used and that is what happens here, in addition to that what happens once again you have y phase double switches and this again you remember there is a zero crossing of y phase.

So, this is again another example of advanced bus clamping PWM, here again you see the double switching phase it switches around the zero crossing, it double switches around the zero crossing of the voltage, but now the phase clamping is different. So, the phase is clamped every phase is clamped during the middle 30 degree duration, this is the middle 30 degree duration in every quarter cycle. So, this is 30 degree clamp and that has been modified into an advanced bus clamping PWM.

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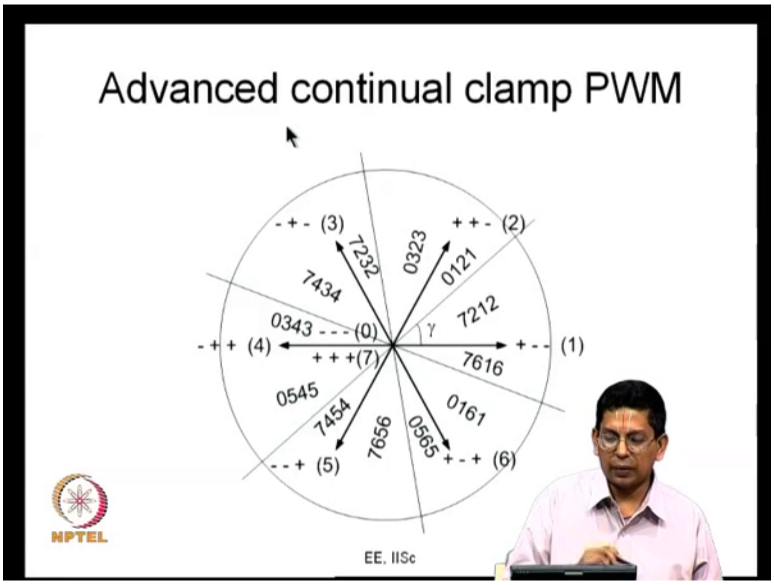

So, now this is advanced continual clamp PWM, this is continual clamp PWM and there is some gamma. Gamma can be anywhere between 0 1 60 degree and instead of 7 to 1 I have written 7212 here, instead of 0 1 2 I have written 0121. So, I will use the sequence of 7 2 1 2 2 1 2 7 it is a trial go on switching that like this and here again I will do 0 one 2 1 0 1 2 1 1 2 and 0 and I will go switch like this.

So, this is what I will do now. In this case what will happens once again a phase will be continuously clamped for a 60 degree duration that is why we call it continual clamp, but a phase will also be double switching once again the double switching is around the zero crossing here. For 60 degrees centered around the zero crossing and that is the reason for calling it as advanced continual clamp PWM.

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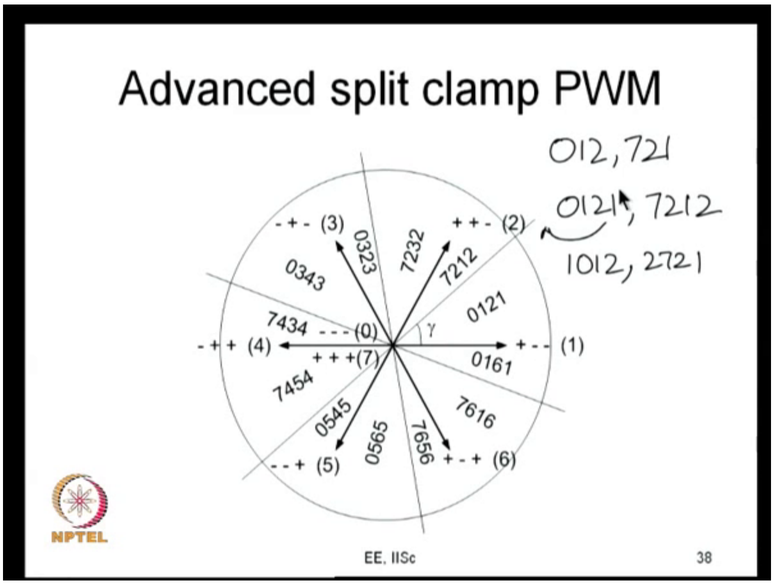

And similarly you have this advanced split clamp PWM, this is the same split clamp 0 one 2 I have replaced by 0 1 2 1 and I have replaced by 7 2 12. So, all that we are trying to do now is we had two possible sequences that is 0 1 2 and 7 2 1.

We constructed our bus clamping PWM using that, now what we have is we have 2 other sequences what we call as 0 1 2 1 and 7 2 1 2 when I say a sequence I include the reverse version of a sequence also that is when I say use sequence 0 1 2 1, 0 1 2 1 is used in one sub cycle and 1 2 1 0 is used in the next sub cycle similarly 7 2 1 2 may be used in one sub cycle and 2 1 2 zone will be used in the next sub cycle. So, now, with these 2 new sequences which I called as double switching clamping sequences, we can come up with these kind of advanced PWM methods advanced bus clamping PWM methods.

So, you had advanced continual clamp here and you have advanced split clamp PWM method here these are not the only sequences though I am not talking about the others right now, there are also 2 other sequences what I can do is I can also apply sequence called 1 0 1 2 that is I am shifting this one earlier I am just shifting this ahead and I can apply this sequence like 2 7 to one right this is also possible I and what I am doing here is in 1 0 1 2 I am applying active state 1 for T 1 by 2 seconds, a null vector for T z seconds active state T 1 for T 1 by 2 seconds again and active vector 2 for T 2 seconds now.

So, 1 0 1 2 is also possible the same way 2 7 2 one is also possible now. In this particular lecture on advanced bus clamping PWM method, I have chosen to restrict myself to these 2. These 2 are the ones that were initially proposed in study and these 2 were proposed a little later and they are they been studied now. So, there are you know. So, you can just all these are I would say is pretty recent well you know something like 0 1 to one was probably tried sometime back in a very different context, but it was not tried out in any big way, all this have gained kind of popularity I would say over a last decade or so. So you know this is I have chosen to emphasize only this later I mean in this module then we do the later modules, when we are trying to analyze current ripple or torque ripple and so on we would try to bring in the other sequences also and do this now.

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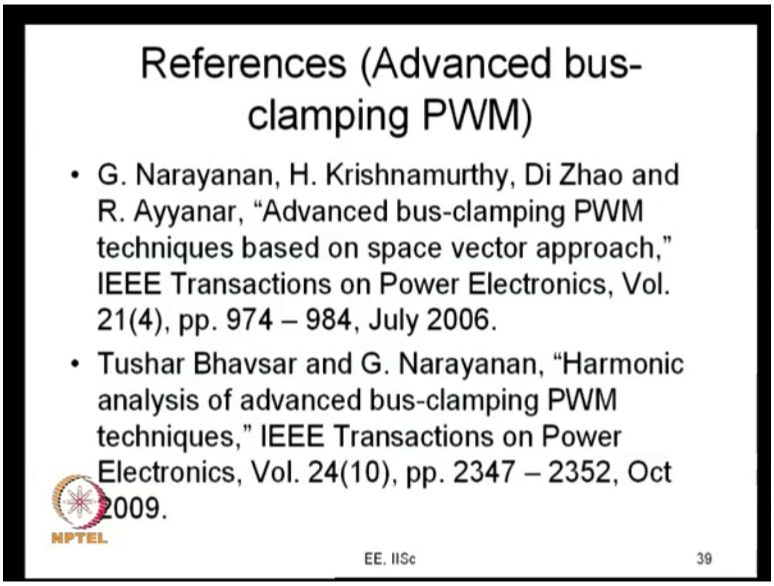

So, I am sure this would not have given this will be given you some idea of what is advanced bus clamping PWM, this base essentially we are relying on these kind of switching sequences, but it is not it would not have given a very very good feel for what it is. So, I am giving you two recent references in this topic, this is Narayanan Krishnamurthy Di Zhao and Ayyanar advanced bus clamping PWM techniques based on space vector approach this is published in transactions on power electronics in July 2006 and I have another paper to tell you this is T Bhavsar and G Narayanan again this is same transactions on power electronics this is in October 2009.

So, these 2 papers can give you further or things on the 2 things that I told you here, this advance continual clamp and advanced a split clamp now I am going to show a few more references now. So, these are the 2 references that I showed and these are particularly about that advanced bus clamping which I discussed today and this is about the double switching clamping sequence trying to look at it from the triangle comparison side.

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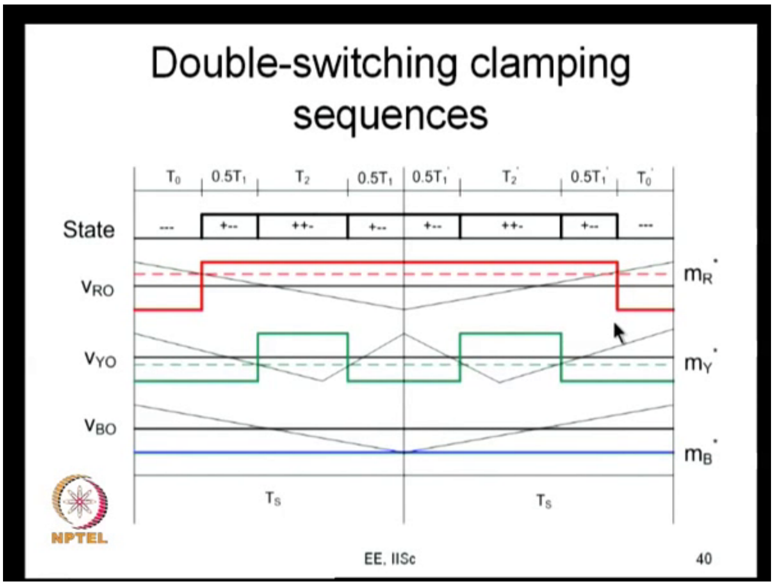

Now you see that here you can consider V R O average and this is m R star this is V Y0 average and this is m Y star, you can compare this with the triangular carrier m R star with a triangle carrier and produce the switching instant now whereas, for m Y star you cannot compare it with the triangular carrier. If at all you want to identify the switching instant it has to be a very complicated signal as shown here now this is not this is a carrier this is your usual carrier whereas, this is not your usual carrier you are using a kind of an asymmetric double ramp signal instead of a single ramp here and this these slopes themselves will vary from one to the other now.

So, triangle comparison is based on comparing a triangular carrier and it presumes only one intersection with the phase in a sub cycle only one switching of a phase, now what we are doing is 2 switchings. 2 switchings of a phase are not possible with triangle comparison method its possible only with space vector approach now.

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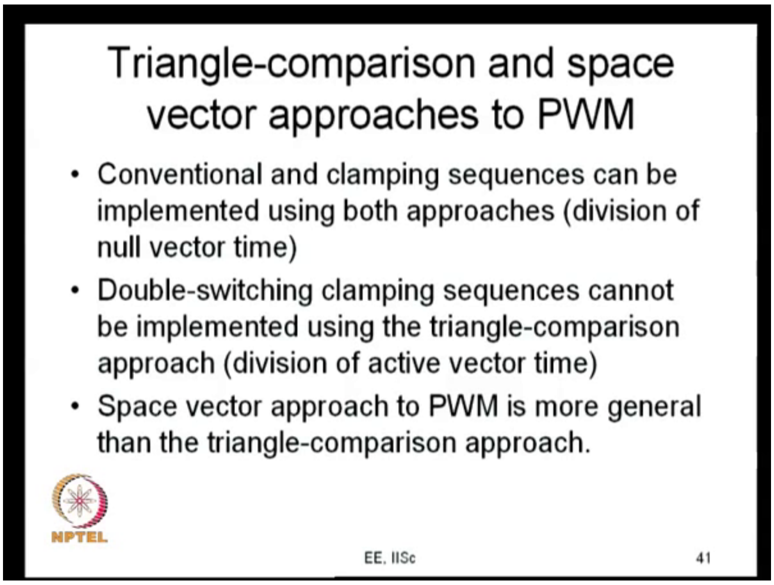

So, I am concluding a few things like this, conventional and clamping sequences many sequences are possible these are possible using both the approaches and division of null vector time is what is essentially done here. Whereas, double switching clamping sequences cannot be implemented using triangle comparison approach, this involve division of active vector time and active vector applied more than twice this is possible only using the space vector approach.

Thus, space vector approach is more general than triangle comparison because it can implement conventional clamping and also double switching clamping sequences whereas, in triangle comparison this is not possible double switching clamping is not possible.

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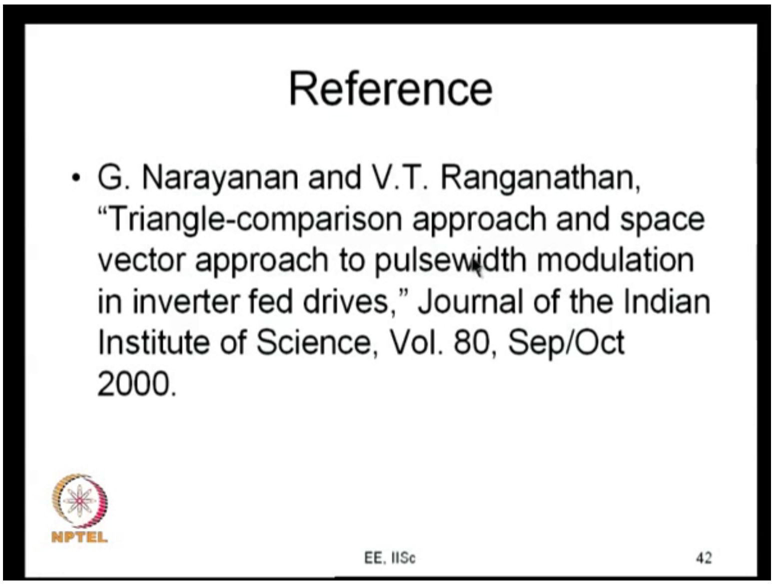

So, you can further read a further about this in this particular reference on the two different approaches right and so these are.

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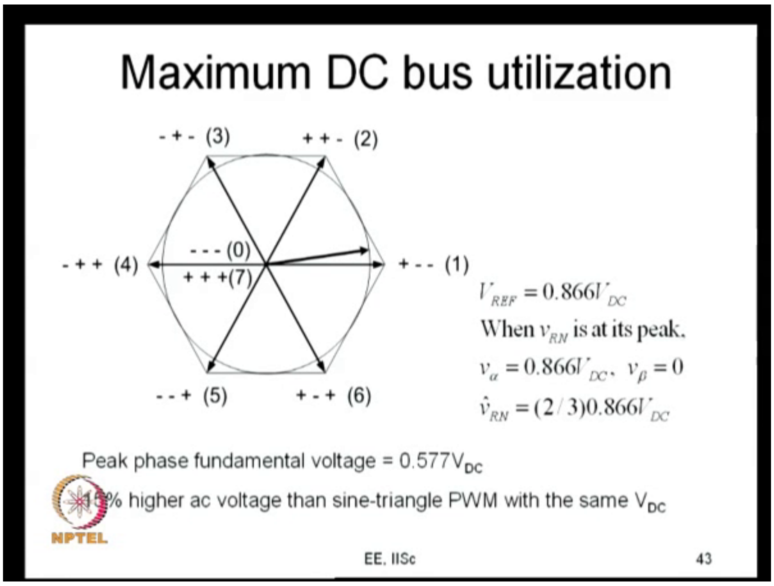

This is about the maximum dc bus utilization that you come to here and by going by the peak value of this I would discuss this later in a next lecture again, you would see that once again the peak phase fundamental is going to be 0.577 V DC which is 15percent higher than this V DC now.

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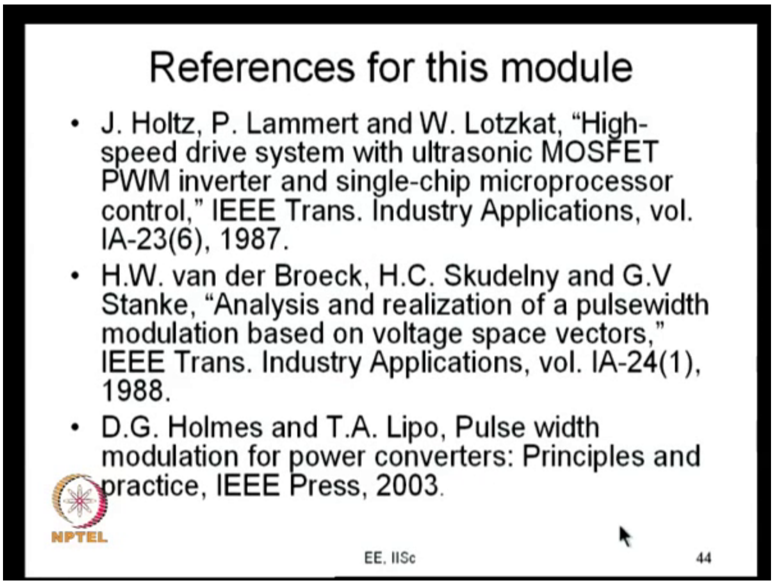

So, these are some of the references I am just reproducing them I have told you earlier about this, these are all about space vector PWM and this is a book on pulsewidth modulation.

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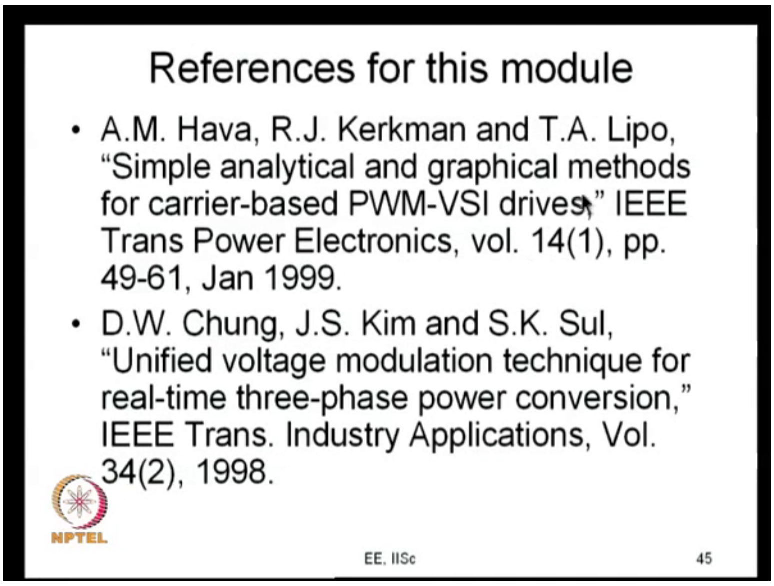

And these are about bus clamping in different kinds of methods, this is about bus clamping how you can view it in the space vector and the triangle comparison methods.

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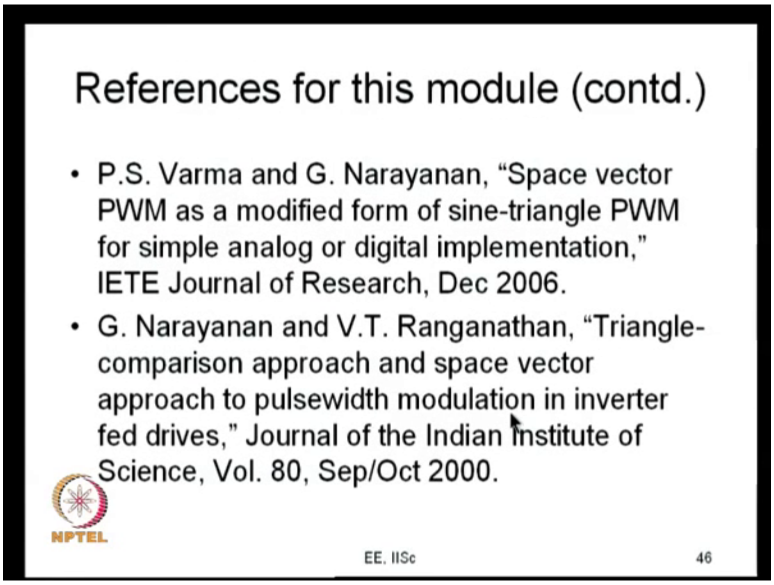

And this one is a tutorial paper I have spoken out to you about all of them earlier I just try to recount here. Thank you very much, thank you for being with me and I will see you again in the next lecture.

Thank you very much.