Pulsewidth Modulation for Power Electronic Converters
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Lecture - 37
Over modulation in Space Vector Modulated Inverter

Welcome back to this lecture series on Pulsewidth Modulation for Power Electronic Converters.

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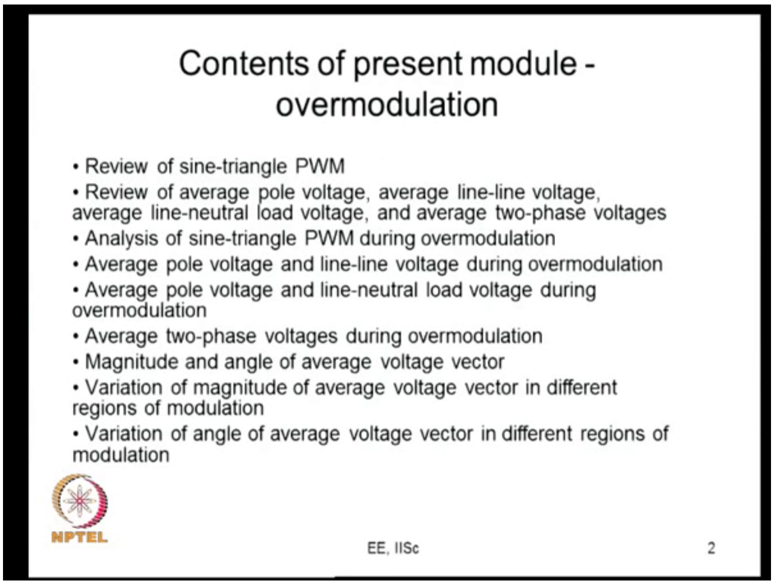

So, we went through various modules, and this is the 12th module that we are going through on overmodulation. So, in the last lecture on overmodulation, we reviewed sine triangle PWM and we reviewed average pole voltage, and average line to line voltage in the inverter. Like, basically this pole voltage is the voltage at the midpoint of a line measured with respect to the dc basement point. Average pole voltage would mean, the pole voltage average over carrier cycle.

Similarly, this line to line voltage is the output between 2 output terminals of inverters say R and Y. And that is averaged over a car sub cycle or a half carrier cycle; that is what you call as a average line to line voltage. Similarly, if you consider a 3-phase star connected balance load, you can look at the 9 line to neutral voltage on the load. And you can take it is average value over ha sub cycle or half carrier cycle. And these 3 phase load voltages, can be transformed into the space vector domain, where they would have 2 components. And they would be the 2 phase voltages.

So, we have reviewed this. And then we started analysing sine triangle PWM during overmodulation. We looked at how does the average pole voltage vary. For example, the variation average pole voltage will be just sinusoidal in sine triangle inside PWM if it is liner modulation. If it is overmodulation, it become it is sinusoidal, but it is a peak clipped sinusoid. So, correspondingly, the average line to line voltages are no longer sinusoidal. They are also non-sinusoidal. There are low frequency harmonic contents here. And a again the line to neutral voltages low frequency harmonics, and it is non-sinusoidal.

So, this 3-phase line to neutral load voltage it can be transformed into 2 phase voltages, and they are also having you know low frequency content harmonic content. And then we started looking at the magnitude and the angle of the average vector. So, what we found was that, the magnitude of the average vector actually starts varying initially; that is when it gets into overmodulation when you know the converter slightly into overmodulation. There is not so much a variation in the angle. The angle of the average vector continues to move more or less linearly with time, but the magnitude starts varying significantly. And subsequently when we come closer to the 6-step operation, what we find is the angle also starts varying significantly when the angle no longer moves linearly with time.

So, it is the angular velocity sometime 0, and sometimes it is faster than the fundamental angular frequency. So, the angle versus time it appears to be a piecewise linear function that is what we saw. So, today what we would do is, we would actually quickly review this part of a sine triangle PWM.

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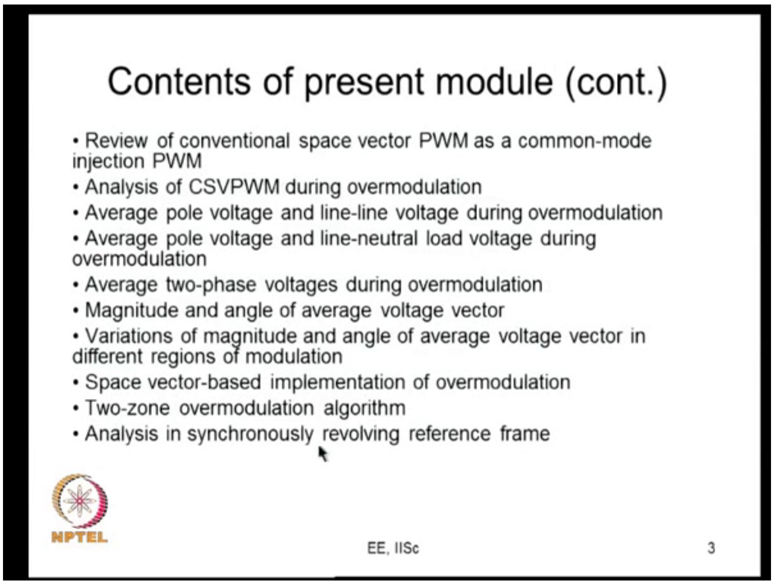

And our emphasis would actually be on conventional space vector PWM. We would first look at conventional space vector PWM as a common mode injection PWM; that is, we have 3 phase sinusoidal signals, and you can add a suitable common mode component, which will ensure that you know this common mode component will ensure; that your null vector time is divided equally between the 0 states; that is what is conventional space vector PWM. We will view that or we will rather review this also. And then you know, we will look at we will analyse conventional space vector PWM doing overmodulation. Just as we did for sine triangle PWM, previously we will do that for CSVPWM now.

So, we look at the average pole voltage and average line to line voltage during overmodulation. Like, what we did for the sine triangle PWM, we will do the same thing for the space vector PWM. So, and we will look at the we 3-phase line to neutral voltages, and will look at that 2-phase line to neutral voltages, after transforming them into space vector. So, these 2 phase voltages in the space vector domain, can be converted into the magnitude angle formed. So, this you can say it is in the so called the rectangular coordinates, you can convert it into polar coordinates; so that you can start seeing the magnitude and angle of the average voltage vector.

So, today we will look at how does the magnitude of the average voltage vector vary. As you know the inverter goes into overmodulation. Similarly, how does the angle vary. So, these are certain things we will see. We will see that there are good similarities between sine triangle PMW and conventional space vector PWM during overmodulation while there are also some differences. This understanding of how these converters behave; that is analyze analysis of the voltage source inverter, operating with sine triangle PWM or convention space vector PWM during over modulation will help us understand how we can implement overmodulation in space vector terms.

So, we will look at what is known as 2 zone overmodulation algorithm. We will also try quickly see like, you know there are some alternative overmodulation algorithms; that is the standard one, there are also other things. We will see if we can do some analysis in this synchronously revolving reference frame. Otherwise in any way this would be you know, we you could also look at the references I will give you references for I will indicate references for all this. The references would certainly talk about these things in good detail.

So, let us gets started with understanding overmodulation. So, I am calling it overmodulation space vector modulated inverter. What I am looking at is I am looking at a voltage source inverter, and I am looking at conventional space vector PWM. So, the conventional space vector PWM can be implemented by adding a certain common mode signal to the 3 phase modulating signals that is what we are going to look at initially. Then we can look at it is implementation from the space vector point of view also.

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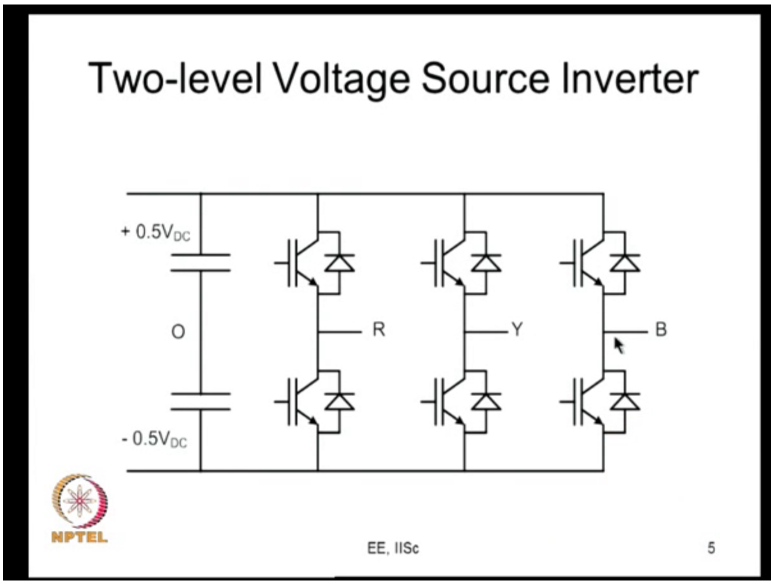

So, alright so this is a voltage source inverter, and this is the pole single pole double throw switch this is pole. The voltage at the pole measured with the respect o s pole voltage V RO. Similarly, you have pole voltage V YO. You have pole voltage V BO. And you can you always have line to line voltages V RY, V YB, V BR. And if you consider the load which is not shown in the picture as a 3-phase star connected load with the neutral point n, then you also have V RN, V YN and V BN alright.

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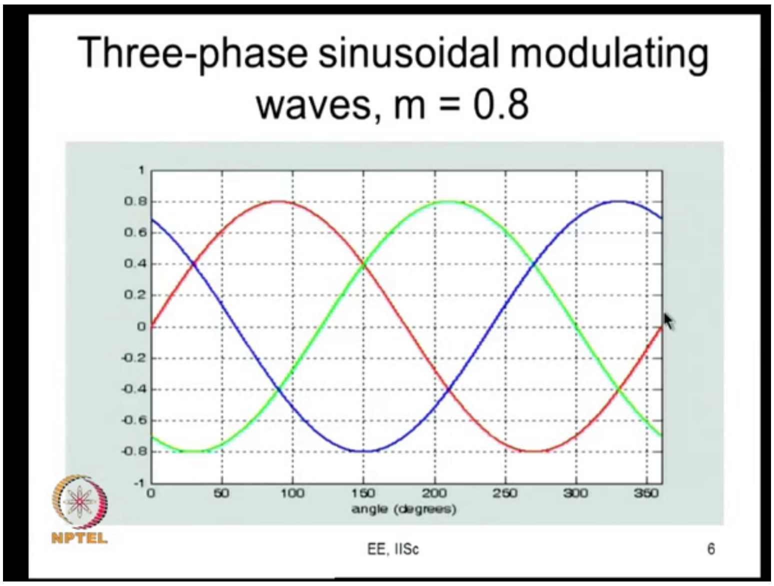

So now if you modulated sine triangle PWM, now we have a sinusoidal 3 phase sinusoidal signal, it is peak is pointed times the carrier peak. So, you have some 3 phase signals like this. And you compare it to the carrier, when the sin is grater then the carrier the top switch of a link is on. When sin is lower than the carrier, the bottom switch is on. That is a convention we have been adopting.

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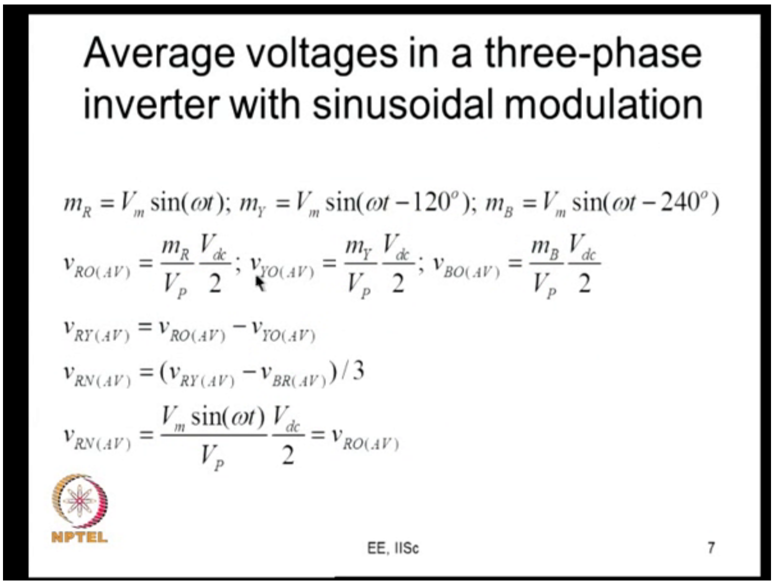

And if you do like this, what happens? You have your average voltages like this. These are the 3 phase modulating signals. The average pole voltages are directly proportional to this, the modulating signal.

So, it is basically these 2 are only scaled versions of the other. You normalise your m R with respect to p multiplied by V DC by 2 you will get your average pole voltage. So, you would get sinusoidal average pole voltages in linear modulation. Again, you are going subtract 2 sinusoids; that is going to result in another sinusoid. These are 2 sinusoids of the same frequency, phase shifted by 120 degree. So, the resultant would be sinusoid of the same frequency, but this will be root 3 times it is amplitude will be root 3 times this amplitude. And it will be phase we know ahead of V RO by 30 degrees. Then you can come up with V RN average. This is the line to neutral voltage on the load. R stands for the load term, while l stands for the load neutral.

So, V RN is the load to neutral, I mean voltage may the load phase to neutral voltage on the load. This you can arrive at by subtracting V RY average minus V BR average divided by 3. So, once again these 2 are sinusoids. And their difference would be a sinusoid. And when you are doing by know this would give you when subtract this from that it is amplitude will be root 3 times that of V RY and when you divide it by 3. So, this amplitude for V RN would be the same as the amplitude of V RO. So, we have V RO sinusoidal V RY will also be sinusoidal, it is amplitude will be root 3 times that of V RO.

And when you do V RY may average minus V BR average you will get something which is whose amplitude is root 3 times that of V RY. Or 3 times that of V RO. Since you are dividing it by 3 you will get an amplitude for V RN average which is same as V RO average.

So, what you will find this you know then there are sinusoids this is sinusoidal this will also be sinusoidal. So, this is what you to get here. So, for sinusoidal PWM when common mode is added here, for m R and that common mode will also be seen in V RO.

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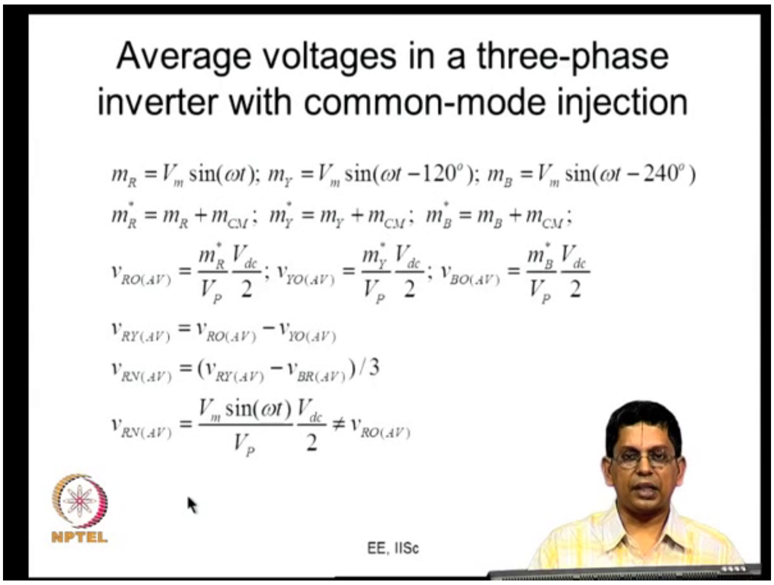

The story is slightly different as we have seen before. So, it is m R m Y and m B are sinusoids, the common mode is added so that becomes m R star m Y star and m B star. And now V RO average is m R star into V DC by V p it goes on like this low.

So, as I have mentioned before, here you know V RN average is not equal to V RO average. Because V RO average would have fundamental plus the common modes, here this will have only the fundamental component. The triplen frequencies will go away. During linear modulation, all this will be alright. Do you will get m R star. So, you know your V RY average and V RN average will be sinusoidal. But what will happen when go into over modulation, that is when m R star goes greater than V p this will get clipped to plus V DC by 2. When m R star goes below minus V DC it will get clipped minus V DC by 2. And therefore, your V RO average will be a peak clipped wave form. So, that is what is would result in distortion as we had seen yesterday.

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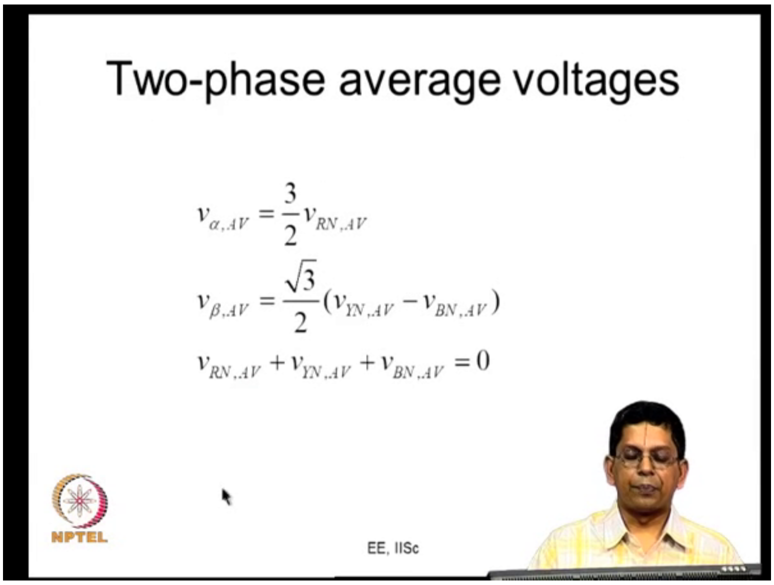

Now, once we have this V RN average V ON average and V BN average, you can transform them into the space vector domain. So, this is V alpha average, and V beta average. We can further square this, and also square this and add the 2 and take a square root. That would give you the magnitude of average vector, but also you can say you can divide V beta average by V alpha average, and take the inverse tan of that. That can give you the angle of the vector.

So, you can also convert this. Here a vector is in the we know rectangular coordinate system. You can look at this in the polar coordinate form. And you can get the magnitude and angle also.

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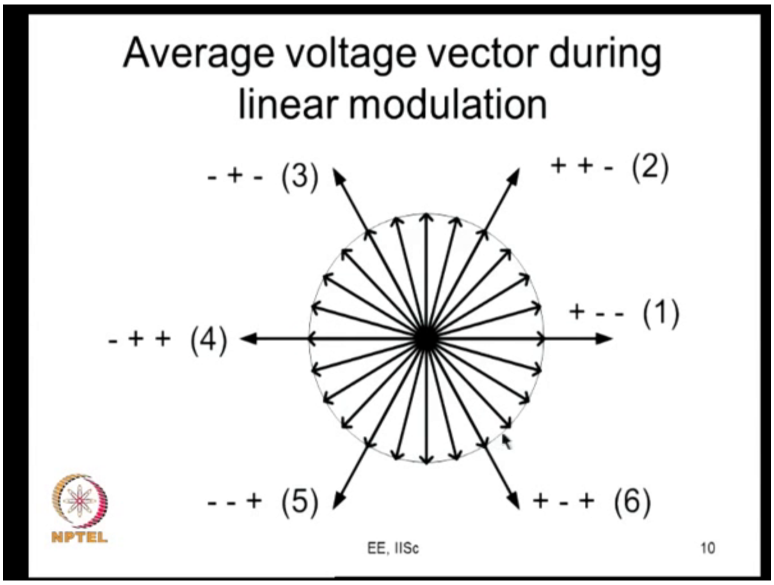

So, if you look at this magnitude and angle, when your inverter is modulating in the linear modulation, what will happen is; every sub cycle it will apply some average vector. That average vectors magnitude will be equal, in all the sub cycles at steady state. And this angle difference between the 2, that will be omega times T sand mould where T s is your sub cycle duration, and omega is your fundamental angular frequency.

So, these angle will be uniform. So, it is like the average voltage vector moving at a uniform angular velocity, and having a constant magnitude. So, this would change when you go into overmodulation.

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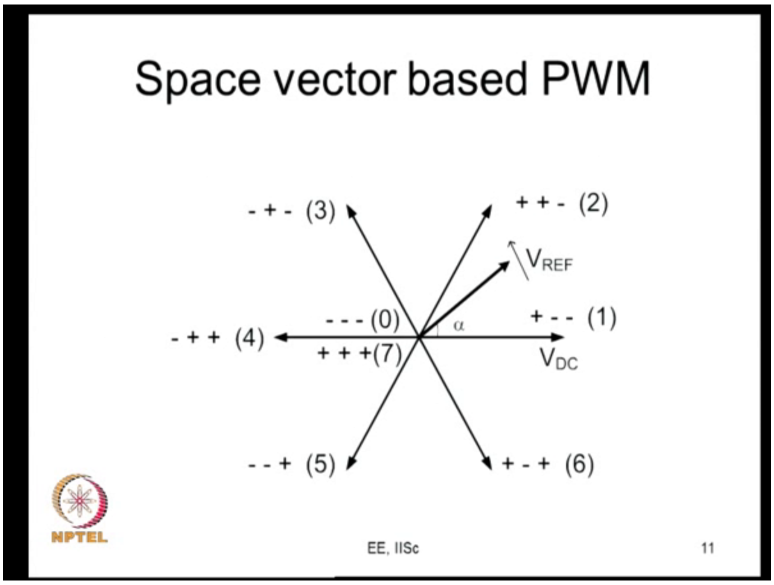

Now, when you are looking at space vector base PWM, what you are trying to see is there is a revolving vector, and revolving vector you are sampling in every sub cycling T s.

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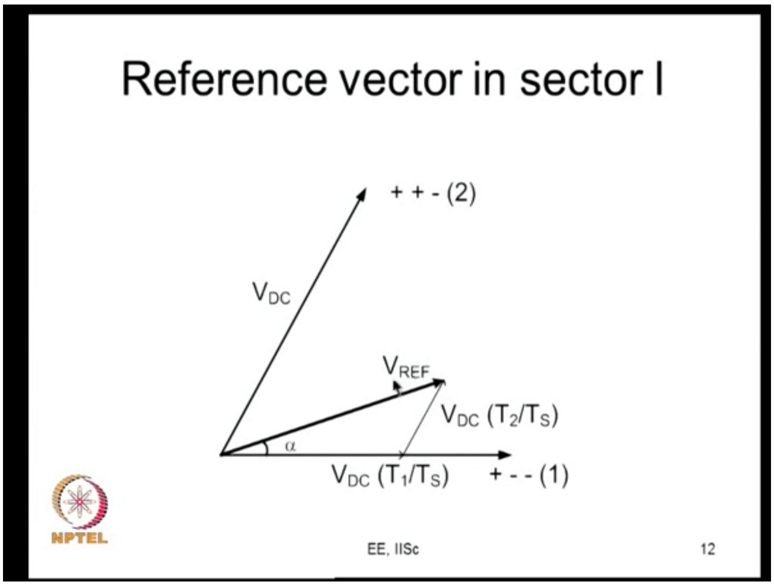

And you get some vector, which is your reference vector. You try to do synthesize this, but I am averaging V 1, V 2 and V z.

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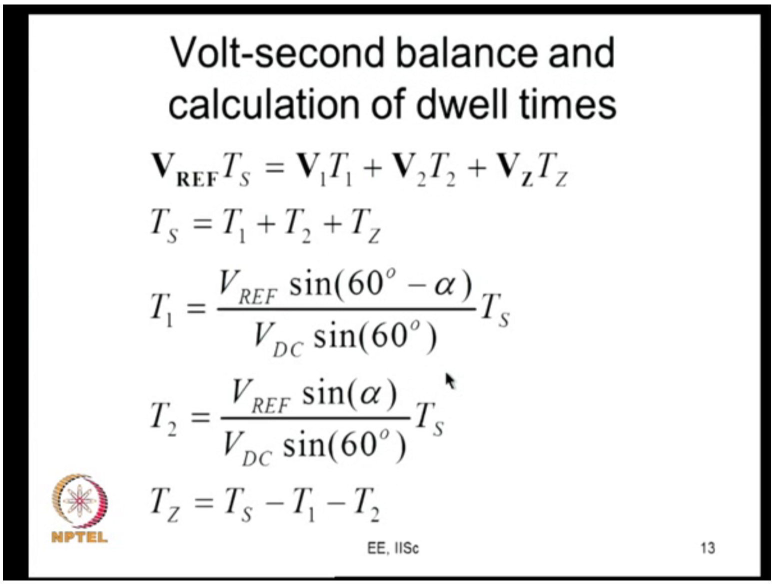

So, how do you do that? As shown in the equation, you apply V 1 vector for T 1 given by this you apply V 2 vector for T 2 seconds given by this equations. And V z vector for T z seconds is given by these equations. So, you will be able to get an applied voltage vector, which will be equal to your reference voltage vector, in an average sense.

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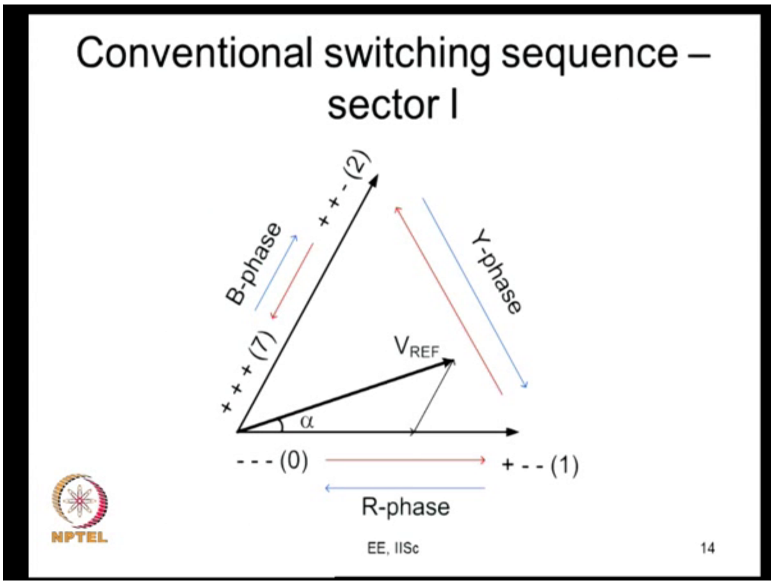

So, in conventional PWM what do you do? This null vector is applied using both the 0 states, and both are applied for equal durations, T z by 2 T z by 2. To you stay for T z by

2 go here for T 1 seconds move here go to T 2 seconds, and come back for T z by 2 seconds and you do the reverse now as you have seen before.

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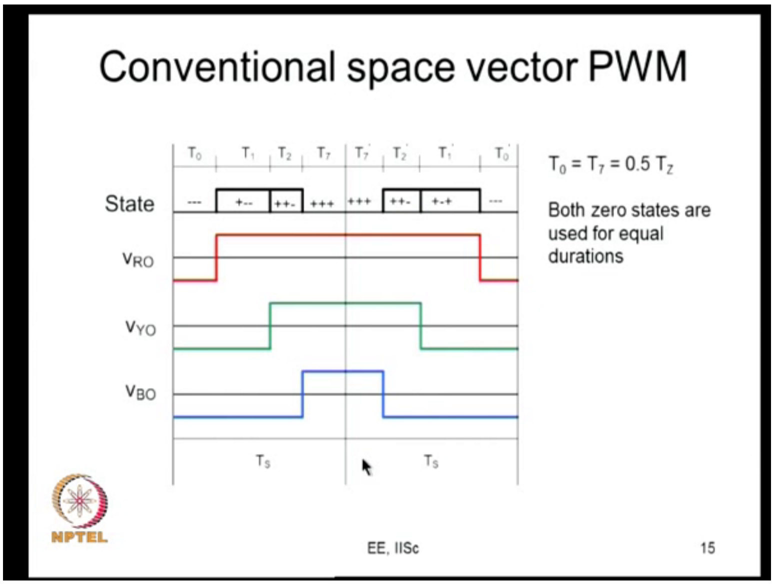

So, same thing is shown here. 0 1 2 7 7 2 1 0, and T 7 is equal to T 0 is equal to 0.5 T z. This is what is conventional space vector PWM. Here you are trying to implement it from the space vector point of view. What do you want effectively achieve is that T 0 and T 7 should be equal.

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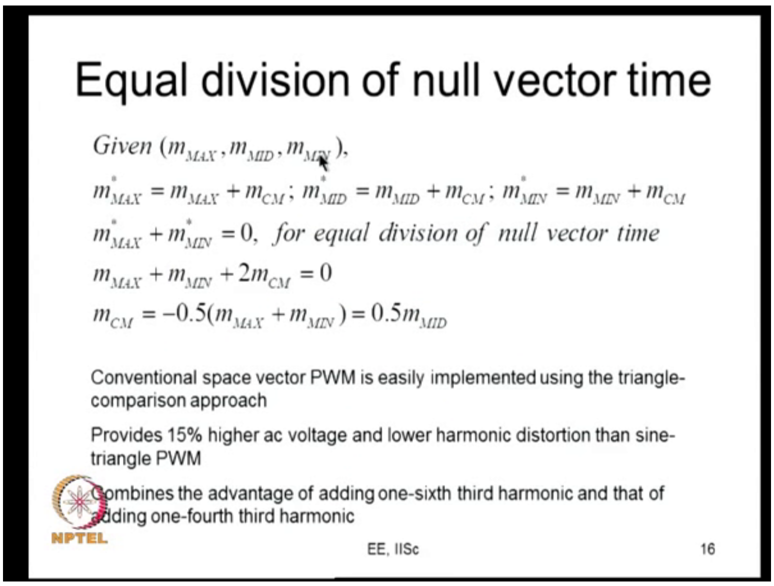

So, you can achieve this by common mode addition also. Let us say you have m R m Y m B. The maximum out of the 3 is taken as m max, the minimum out of the 3 is taken as m min. The middle value out of the 3 is taken as m mid. So, m max would be the highest one m min would be the most negative one, and m mid will be close to 0, be closes to 0. If you take the unsigned values, m mid will have the lowest value.

So, you call the m max and m mid and m min. Now you add certain common mode voltage, let us call it m CM so that you add it m max m med and m min. So, you get m max star m mid star m min star which are the modulating signals you are going to use. Now if you want your null vector time to be equally divided, then you need this condition m max star and m min star should to be equal in amplitude, but opposite in sign. They should be equal in magnitude, but opposite in sign, our m max star plus m min star is equal to 0.

So, if you need that then m max plus m min plus 2 m CM is equal to 0, as we have done before. And this gives you the expression m CM is minus 0.5 times of m max plus m min. And now m max plus m min is equal to minus m mid. Because you start from 3 phase sinusoidal signals and therefore, m CM is equal to 0.5 m mid, which is what we have been using. So, you can actually you know by if you have 3 phase sinusoids you can generate common mode like this. And you can add it all the 3 signals and then you do your triangle comparison and generate your PWM.

So, this will ensure equal division of null vector time. This is an easy way of implementing conventional space vector PWM, rather than going through the space vector approach, where you have to have a revolving vector you have to find out which sector it is in and then we know you have to calculate T 1 T 2 which involve trigonometric functions. And so, that some computational complexity involved whereas, here this is simple comparison which can be implemented in many you know, timer based implementations where it is easy for even like in d s p and all that where it is easy to implement here.

So, you use this triangle comparison approach. And you see that by this of addition you get 15 percent higher voltage also than sine triangle PWM etcetera. So, this is something we had seen before.

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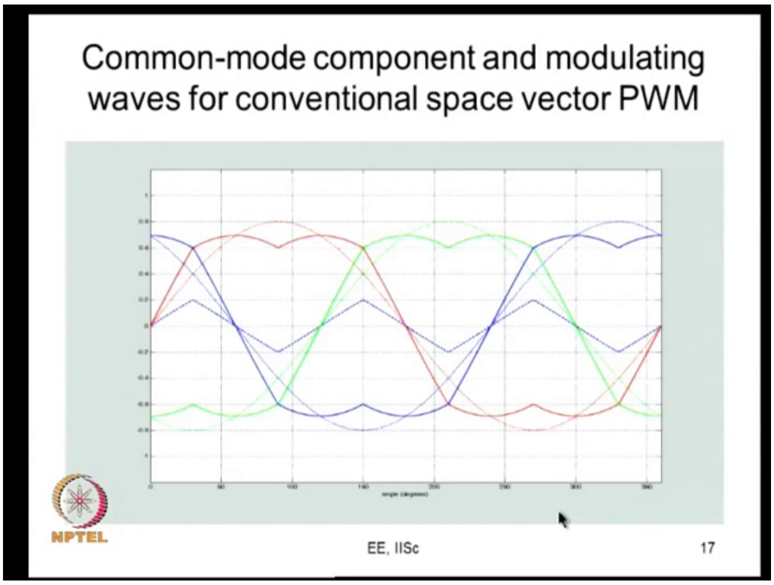

Now, that is what we are going to use now. What we do is if you have m R m Y and m B of amplitude peak value point at tends the triangle, we are adding common mode. So, the common mode signal is this blue signal. When you add that what happens, this m R becomes is m R star as shown by this line. And you can see that the peak value of m R star is significantly lower than the peak value of m R. So, this increases your dc bus utilisation.

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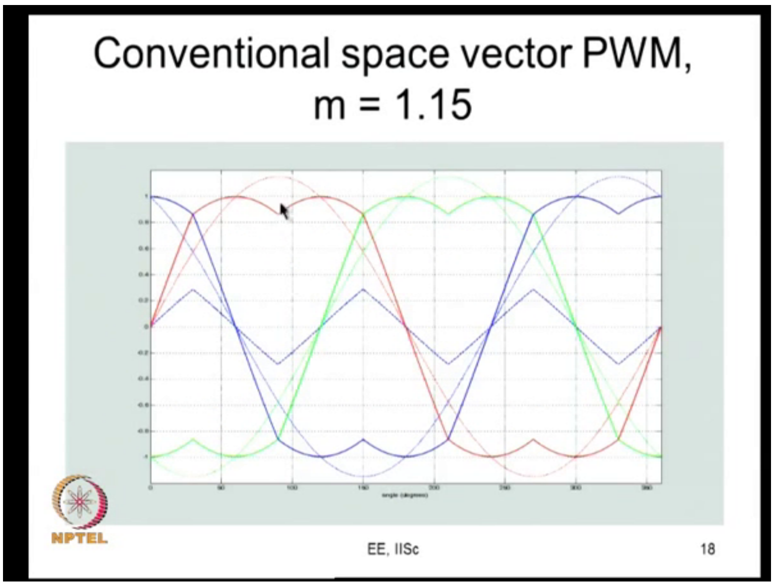

So, if your m R goes to 1.15 your m R star just touches 1. 1.15 more precisely is 2 by root 3; so our reciprocal of root 3 by 2 which is sin 60. So, you see that here it touches 1, and m R star just touches 1 whereas, m R s the peak value of m R is actually higher than 1 that is 2 by root 3. So, this is what is a responsible for the 15 percent higher dc bus utilisation. And so, this is conventional space vector PWM giving you higher dc bus utilisation.

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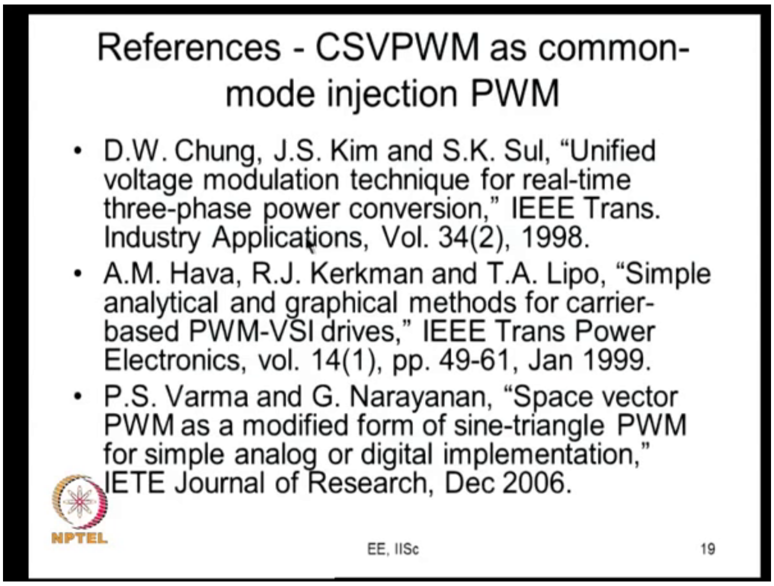

So, there are as I have also discussed this already, but this is just a quick review of that. So, there are good references this is a good paper on this where he talks of the null vector time division and how the different things are I mean PWM methods it continuous and discontinuous PWM methods, you get a distortion on that.

So, you use the 3 phase modulated signals to find out your activity time etcetera. So, this is a good reference this is a another reference, which also talks to you talks about how do you generate common mode in the various cases for continuous and the discontinuous PWM methods. And this is tutorial papers essentially on this conventional space vector PWM how you can we add, conventional space vector PWM as a modified form of sine triangle PWM.

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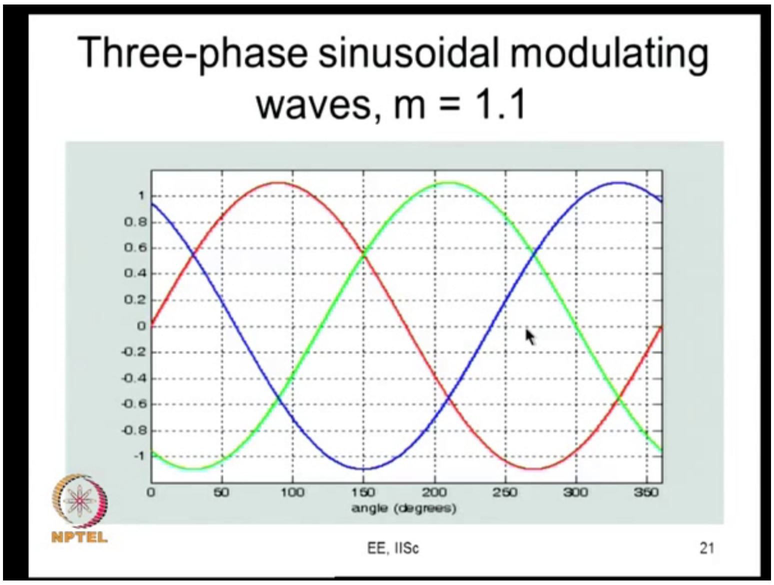

So now we are going to look at this can CSVPWM as a common mode injection PWM for this part of that. So, before that we would like to review what we did in the last class on analysing the sine triangle PWM.

So, let us say we take 1.1, you know 3 phase sinusoids of amplitude 1.1 times the peak of the carrier. So, it goes into overmodulation.

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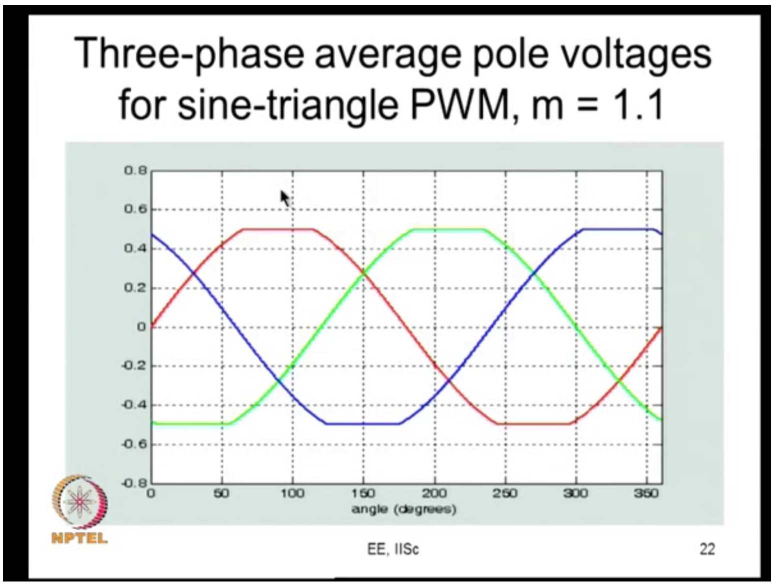

So, what happens? The V RO average is clipped it is clipped to 0.5 V DC it is clipped minus 0.5 V DC. V YO average and V BO average are similar, just phase shifted by 120 degree and 240 degree respectively.

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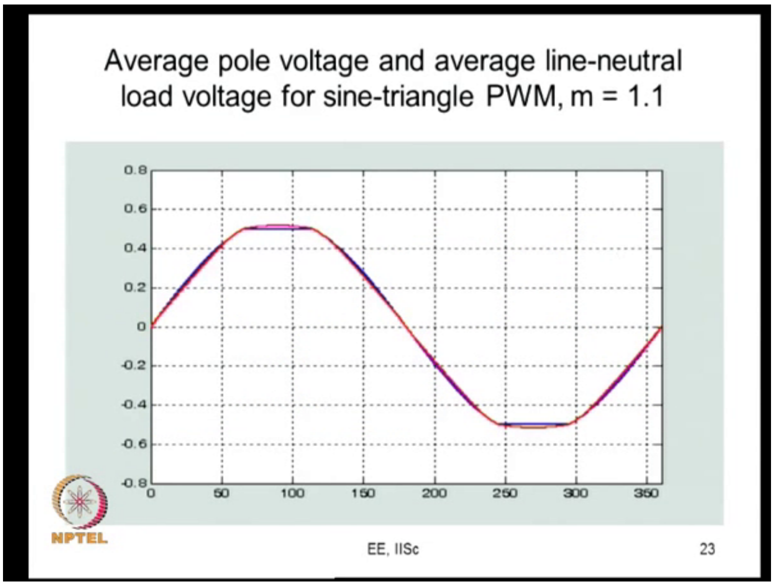

So, what happens? You get your V RN average. So, from V RO minus V YO you can do and then you can come to V RN. So, V RO average is shown by the blue line, and V RN shown by the red line. There is a small difference between the 2. We as I mentioned yesterday repeatedly that V RN average would not contain triplen frequency components. Whereas, V RO average would contain, if it V RO average had been sinusoidal it would contain nothing. But once it is peak clipped sin it will have third fifth 7th all these harmonics. And the red wave form will not contain third ninth etcetera, but it will contain fifth 7th 11th 13th etcetera.

So, the red wave form is your V RN average. Similarly, you will have V YN an average in V BN average.

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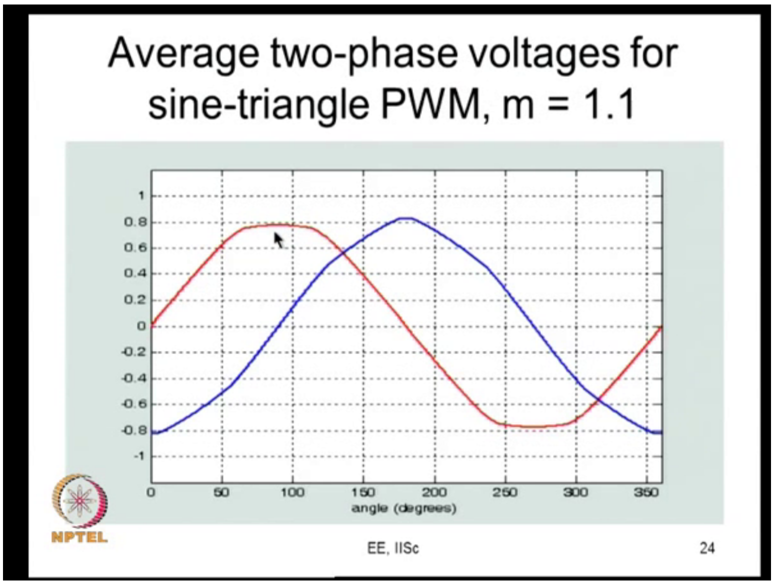

If you transform them into the space vector domain, you get your V alpha average and V beta average. You can clearly see that these are not sinusoidal. There is considerable distortion here, alright.

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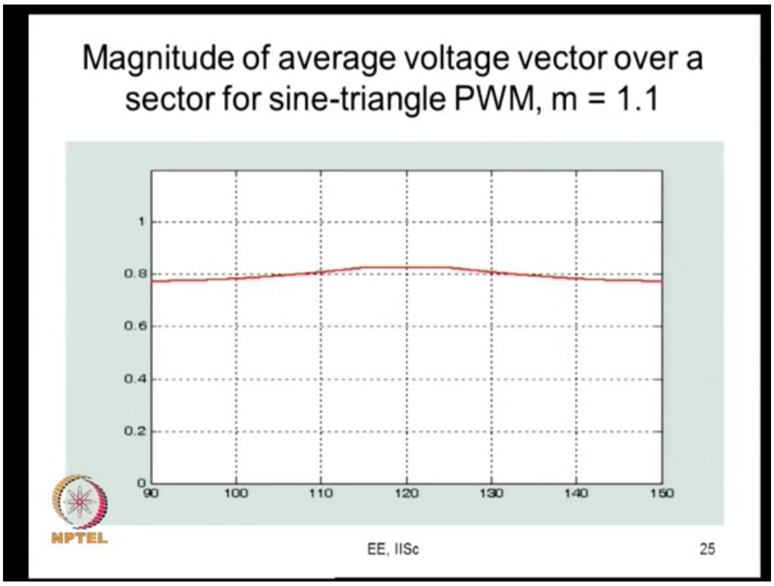

So, if you look at the magnitude of the vector, it is a little above 0.785, which is pi by 4. And if the here it is find close to 0.8. It goes a little above and below that. So, the magnitude varies this is how the magnitude varies over a sector. And this repeats over every sector.

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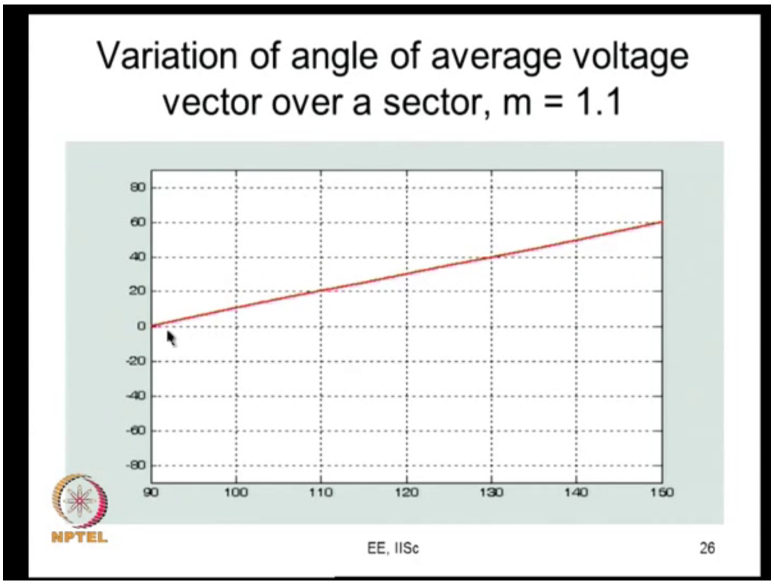

And how does the angle change the angle change from 0 to 60 degree of the vector?

So, the average vector continues to move linearly with time, it is angular velocity continues to be constant. Whereas, the magnitude is a little it changes that goes up and down anyway you mean it varies.

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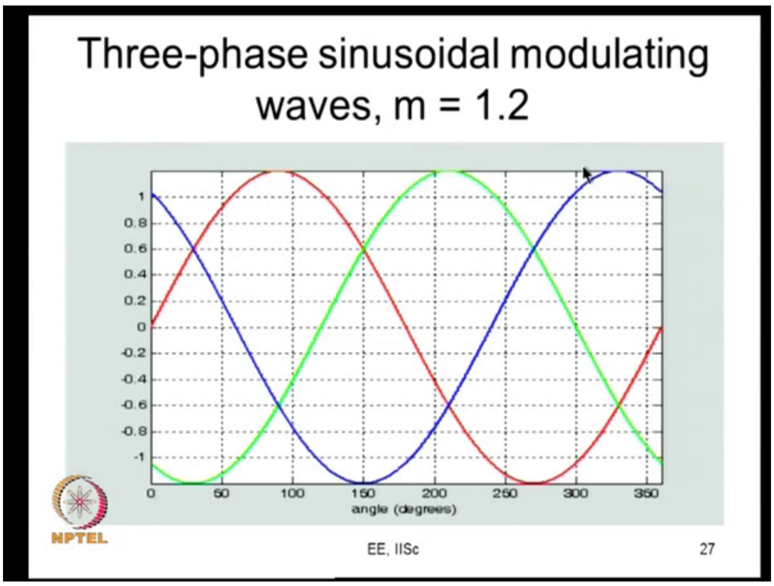

So, this is at m is equal to 1.1. You go into deeper into overmodulation when you go just little deeper into m is equal to 1.2. Now you see that you are going above this for a considerable length of time this much longer than 60 degrees. You go into over modulation. So, and also when it is overmodulation R phases an overmodulation here our R phase modulating signal is exceeding positive carrier B phase phaseis exceeding, I mean going below the negative carrier here; similarly, when R phases phaseexceeding the positive carrier here the yellow phase phaseis going below the carrier here for a short while.

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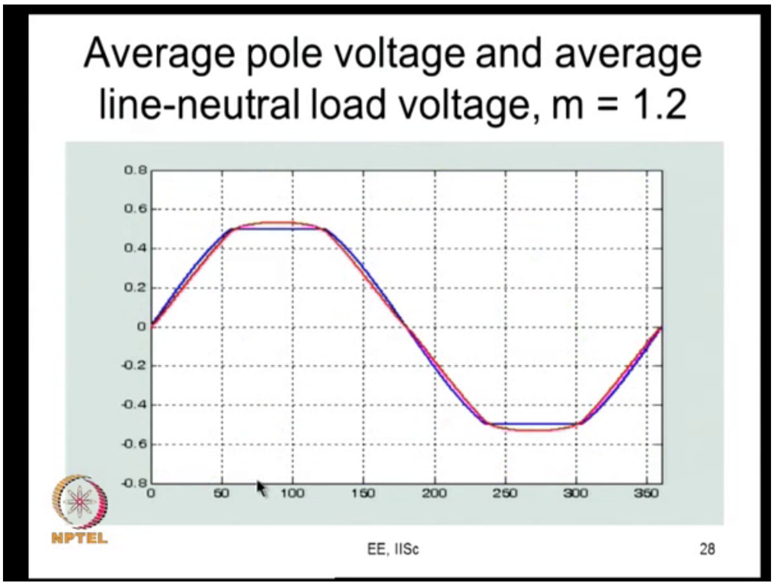

So, these kinds of thing happen, and you also see you now you know the clamping duration is longer. You would find 2 phases clamped concurrently at times. Now you have this V RY average, which is the V RO average. Average pole voltage the blue waveform, and this is the V RN average; that is the average phase neutral voltage applied on the load, that is the red voltage. The red voltage does not contain triplen frequency components, and that V RN average the red voltage. You have the similarly you would have V YN average and V BN average.

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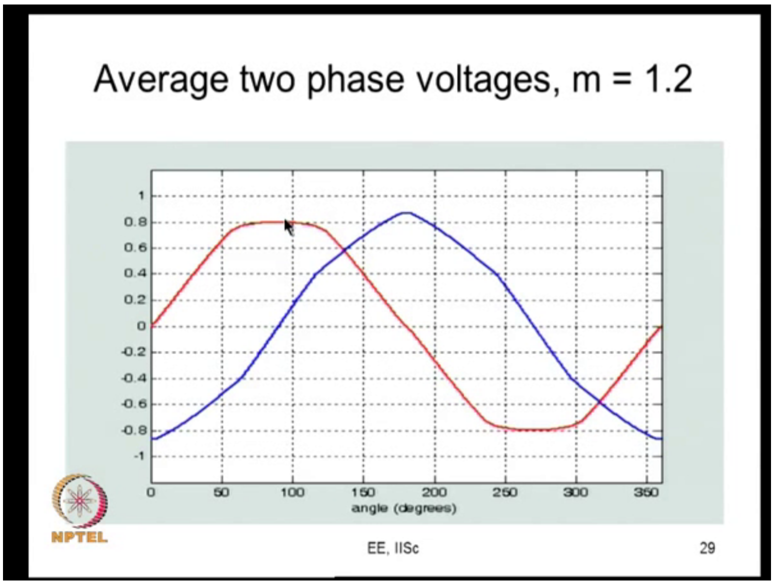

We transform them into the space vector domain to get your V alpha average and V beta average, V alpha average would have the same wave shape as V RN average just a scale factor of 2 by 3.

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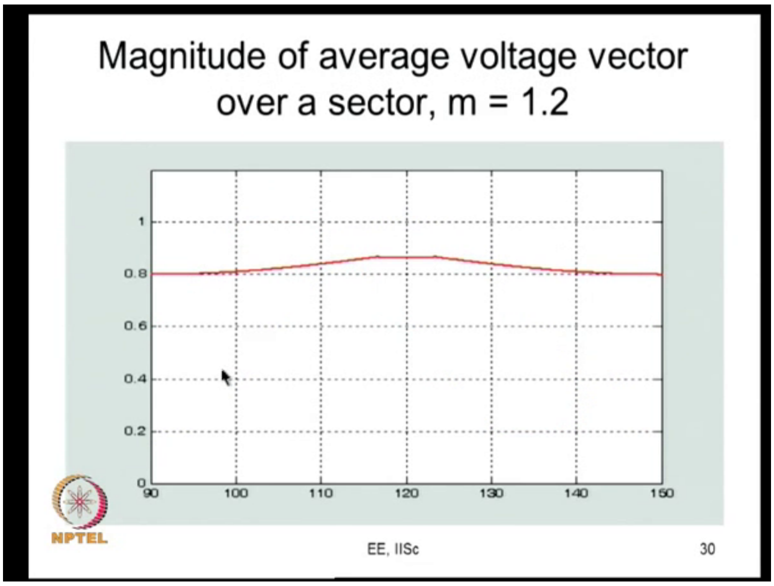

So, you have this you see that there is more distortion than we saw before, and you can see that the magnitude has increased a little. Earlier it was going below 0.8 and above 0.8. Now it is all above 0.8. So, the average over value is above well above 0.8, but you see that you there is a clear error in the magnitude, which is very visible. It is low, and it is high the variation of the magnitude is more clearly visible than at m equals 1.1.

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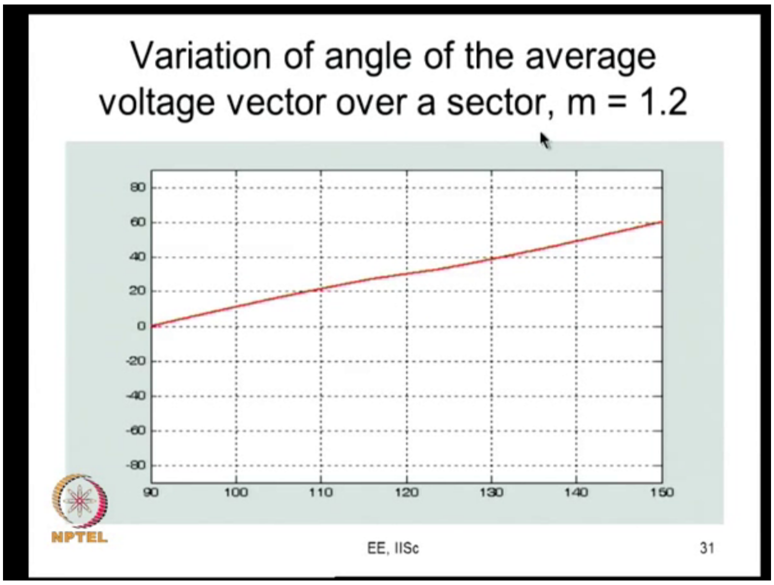

The angle continues to be more or less linear with time of the average vector.

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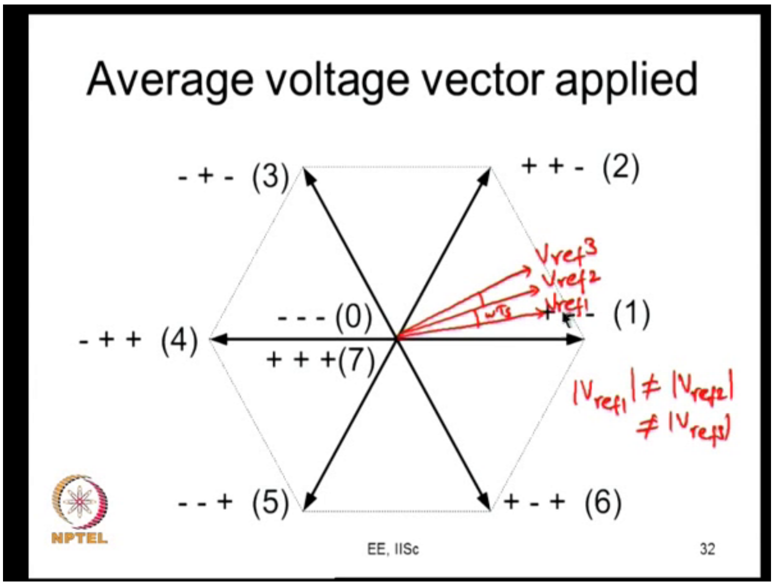

So, what we can say is; you have a situation where we are applying vectors like this where we are applying vectors like this.

Let us call this V REF 1 as a vector which we are applying in one sub cycle. V REF 2 as the vector we are applying another sub cycle, V REF 3 as the vector we are applying in the next sub cycle. What we have is as I said yesterday; V REF 1 is not actually equal to V REF 2. Again, that is not equal to V REF 3, there are variations in that; however, this angle and this angle they are equal. These are equal to omega T s roughly. This is the scenario that you have here when you are doing overmodulation, with sin triangle PWM.

So, you will see that it is improved when we go into conventional space vector, PWM it is a little different from here. There will be a variation in the magnitude, but it will follow the hexagon and the circular trajectory.

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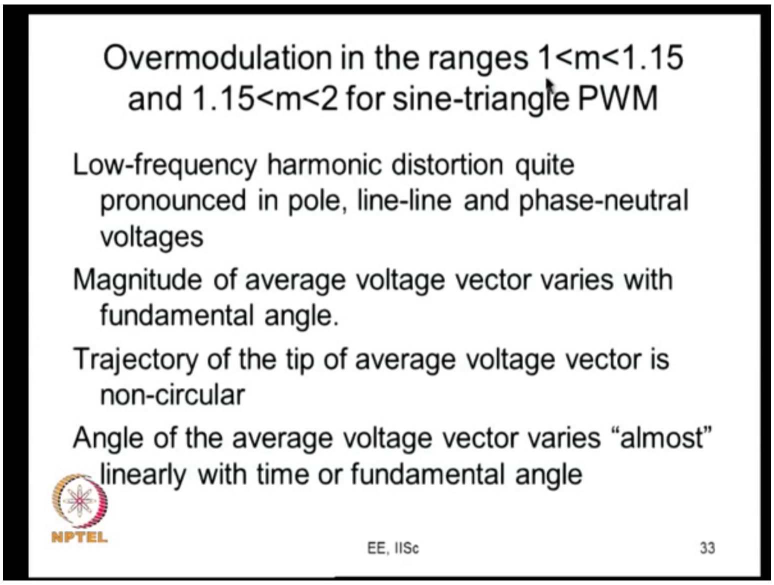

Before that let us look at that one, take this sin triangle PWM 2 ranges; one between one and 1.15. So, here at anytime only one phase modulating signal will go above or below the peak carrier peak. And the other range 1.15 to 2. In this you would find 2 of them going above. Sometimes only one modulating signal would go above the carrier peak, or sometimes you would have 2 of them going beyond the carrier peak one above the positive carrier peak and one below the negative carrier peak.

So, these 2 ranges if you look at, what do you see? You see that the low frequency distortion is quite pronounced in the output voltage inverter output voltage. Be it pole voltage line to line and the phase neutral. The main difference in the pole voltage you may have, triplen components and phase neutral you will not have that is the essential difference. And this phase to neutral voltages these the 3-phase voltage can be transformed into the space vector domain; and if you look at the magnitude of the average vector that varies with the fundamental angle. The trajectory is not circular. That average voltage vector applied in various sub cycles, if their magnitude are equal the trajectory of the tip of the vector would be circular.

Now, it is non circular; however, the angle of the voltage vector varies almost linearly with time. That is not a very appreciable change if there is there is some change, but that could be ignored.

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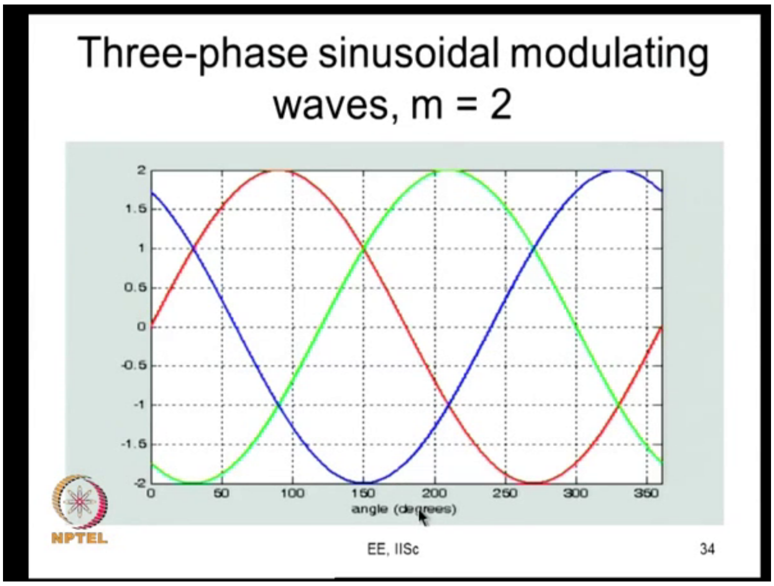

So now let us say if you go into m is equal to 2, which is that end half what I said here. So, when you go to m is equal to 2 what you find is for 120 degrees, this R phase carrier signal modulating signal is above carrier positive. Here for 120 degrees it is below the negative. So, that is at 30 degrees itself it crosses 1. So, from 30 to 150 degrees it is above the positive peak. Here again from 210 to 330 degree, it is below the negative peak.

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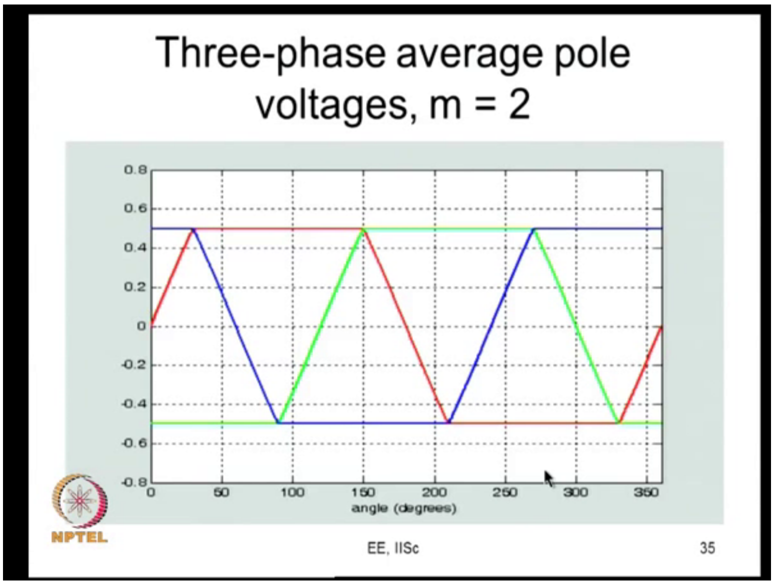

And therefore, your average pole voltage for R phase is like this, looks like a trapezoidal wave form because this part of the sinusoidal is more or less a straight line.

And so, you have the average pole voltages for the Y and the B phases now. So, 2 phases are clamped concurrently R and Y phase, R and B phase, Y and B phase, Y and B phase here B and R I mean this is Y and R phase B and R phase. So, at any instant you find that any carrier cycle you will see 2 of them are clamped.

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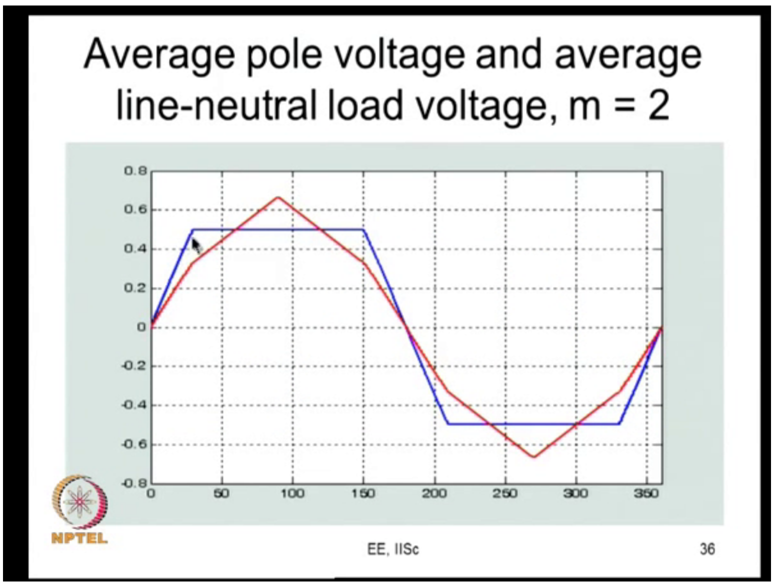

So, your resultant you know this is the average pole voltage for R phase, the average line to neutral voltage for R phase applied on the load is a little different like this. And a so, because this red wave form does not contain that triplen components, it looks a little closer to this sinusoid. So, you can see this now.

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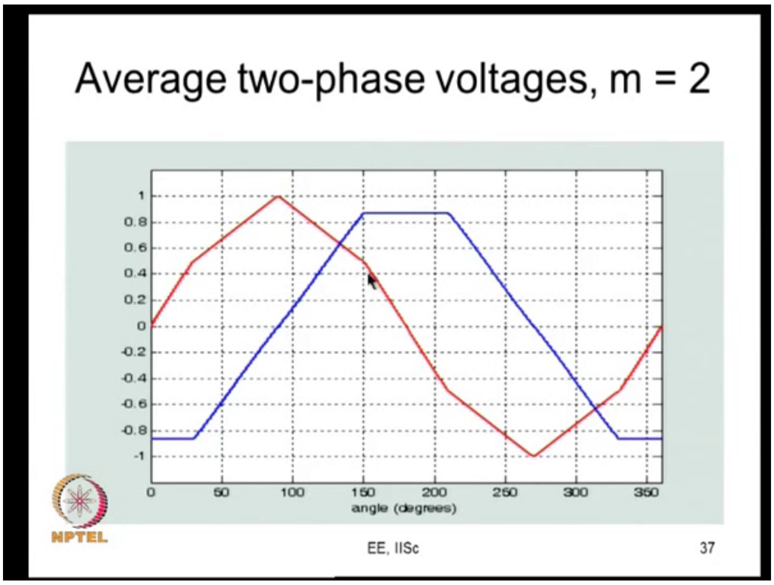

So, you can transform that V RN average if you look at the voltage vectors, you know the 2 components alpha and beta axis components of the average voltage vector, the alpha component looks like this, and the beta component looks like this.

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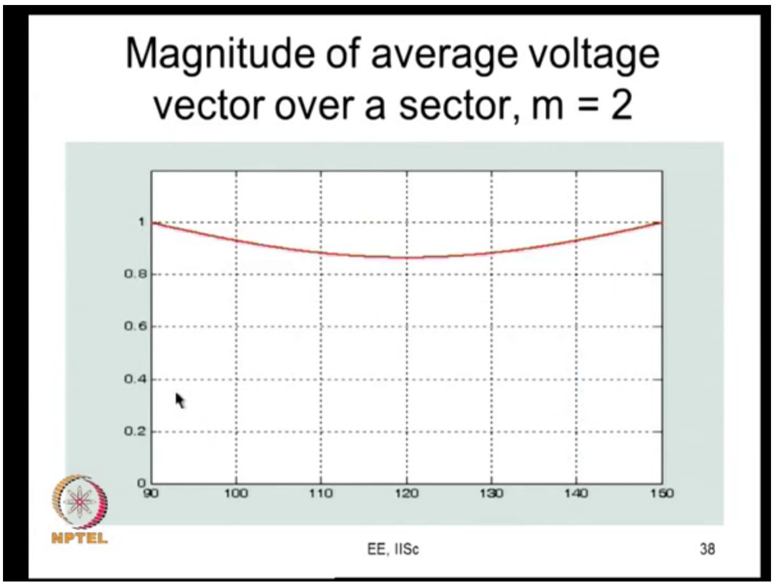

So, if you look at the magnitude, you can see that there is a significant reduction in the magnitude. Sometimes the magnitude becomes equal to 1, one stands here for V DC. That is here be active vector is getting applied, and once again the active vector is getting applied here.

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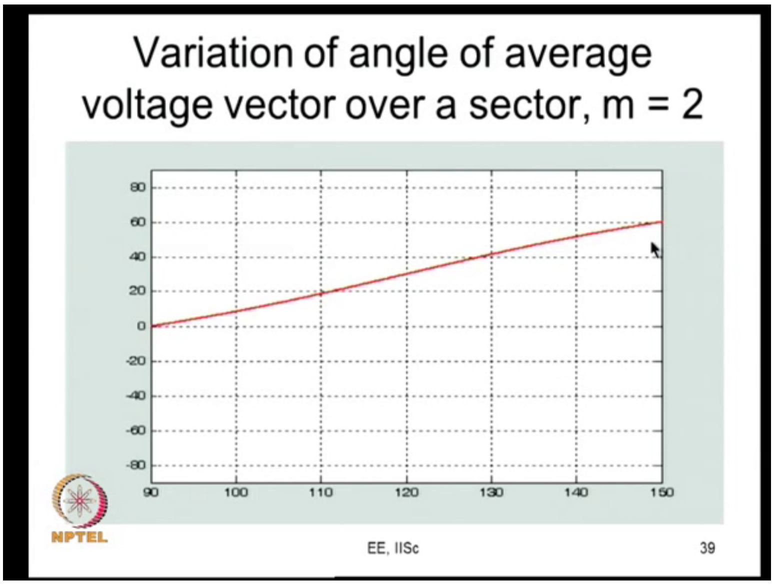

So, if you look at the angle the angle still more or less a straight line. You can actually plot a straight line from here to here, and you may find a small variation, but that variation can actually be ignored.

So, you can still see that the angle varies, the angular velocity of the average voltage vector is still more or less a straight line.

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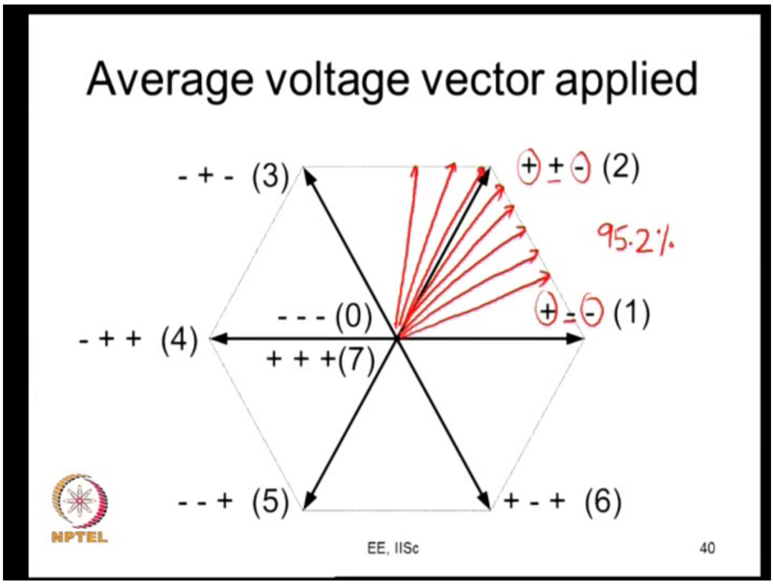

Now, but now what happens as I said we 0 vector is never getting applied. 2 of the phases are always clamped which 2 phases can be clamped if you look at here, Y phase can never be clamped in sector one. On the other hand, R phase can be clamped, and B phase can also be clamped. So, what actually is happening is; you are applying voltage vector like this, in one sub cycle. In the next sub cycle, you might apply voltage vector like that.

This is in the third this is in the subsequent once. So, the voltage vector the average voltage vector applied are all like this. They all go and touch the tip just touches the hexagon. So, what happens? To produce this vector, you are not applying null vector. You are only applying active vector 1 and active vector 2 for different periods of time, only one phase switches mainly this phase switches now.

So, the trajectory when you go into this m is equal to 2 is entirely on the hexagon. So, at this point of time you know if you see the voltage percentage you will get would be like 95.2 percent of this 6 the portage is what you will get. Analysis will show this, this is there in the references also, alright.

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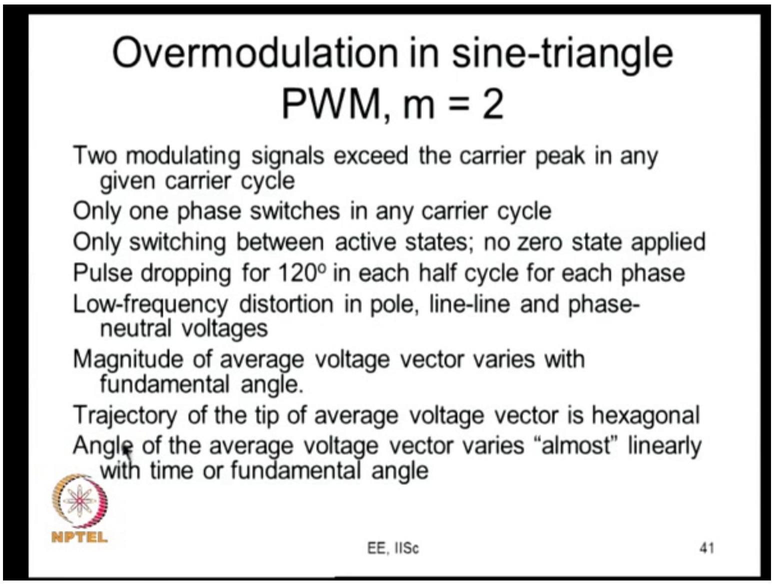

So, what if m is equal to 2? 2 modulating signals always exceed the carrier peak in any carrier cycle. Only one phase switches. This is switching between the 2 active states. So, no 0 state is applied pulse dropping for 120 degree in each half cycle for each phase. You have a high low frequency distortion. And you know magnitude of average voltage vectors varies, but now the trajectory of the tip of the average voltage vector is hexagonal. But you still find that the angle of the average vector as almost linearly with time on the fundamental. So, when you go beyond this this would start changing now.

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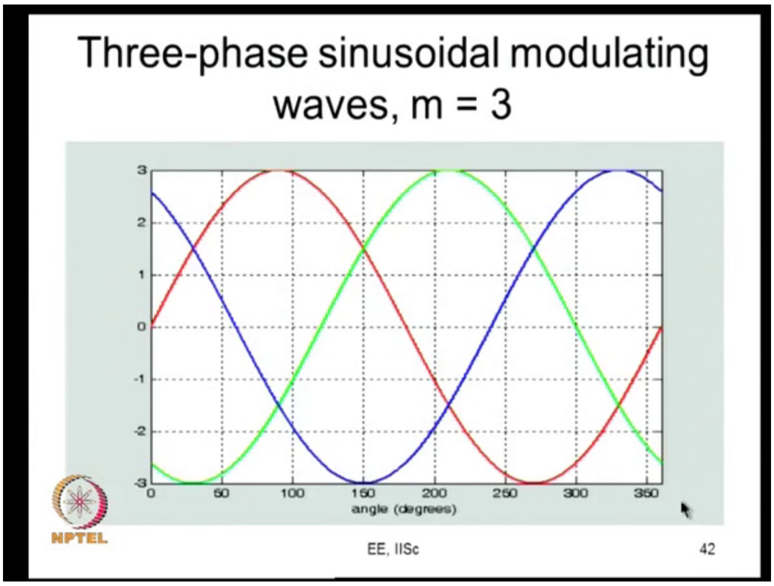

So, if you look at m is equal to 3, it is crossed the carrier peak here itself. And it goes well above that. So, you know it is very short interval, that it is within the carrier peak here, again it is for a short interval. So, R phase will switch here will switch here, R phase would not switch between this. Again, it will switch here, and it will switch here. It would not switch in this interval. So, your pole voltages would look like this.

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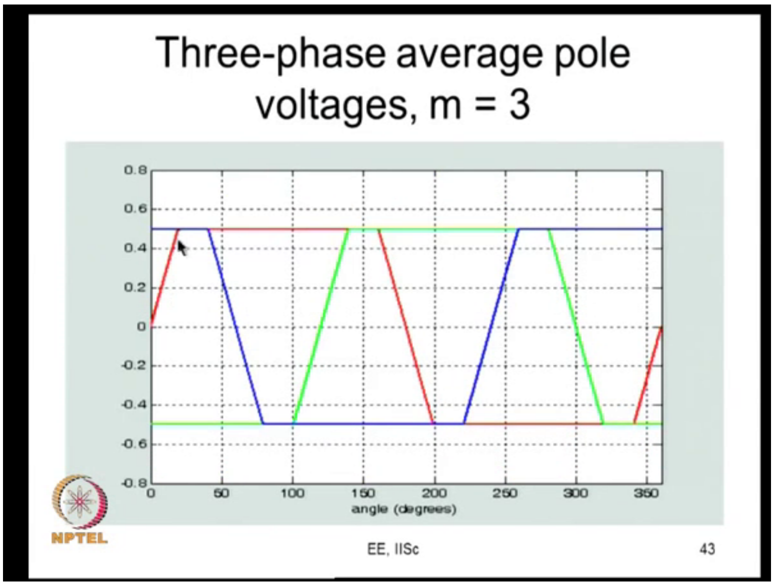

There the average pole voltage is equal to 0.5 V DC for a duration longer than 120 degree. Here it is equal to minus 0.5 V DC for a duration longer then much longer then 120 degrees.

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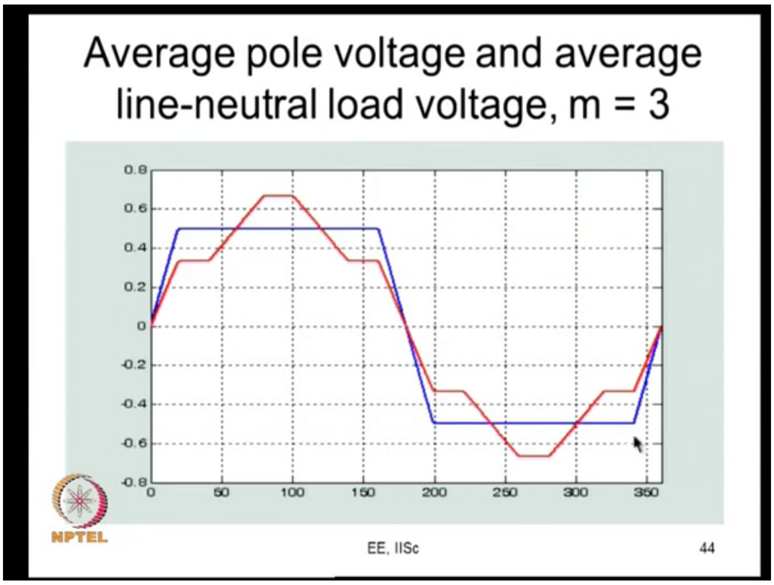

If you look at your average pole voltage it is like this, the average line to neutral V RN average is like this. Similarly, you will have V YN average V BN average.

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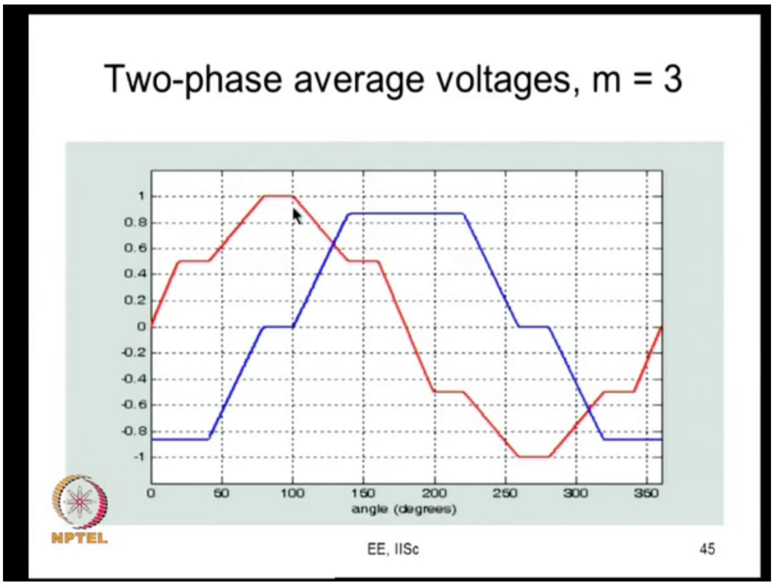

You transform them into the space vector domain you get your V alpha average, you get your V beta average.

So, you can see V beta average is flat for very long time, and you can see V alpha average is also flat. So, when the 2 are flat what does it mean? V alpha average is also constant V beta average is also constant. Actually; that means, that you know there the vector magnitude is constant. So, V alpha average is 1, V beta average is 0. 1 square plus 0 square, under root is 1. So, what is happening is your actually applying the active vector incidentally. It is the active vector 1, and you know that is what is applied in all the sub cycles in this region. And you look at here, you what you have is actually 0.8 6 x root 3 by 2, what you have 0.5. You square this plus you square this, you will get again 1.

So, you are applying here again you know the vector magnitude is 1. You are actually applying active vector 2. Here you are applying active vector 3 that is why your V alpha average and V beta average are constant over those sub cycles now.

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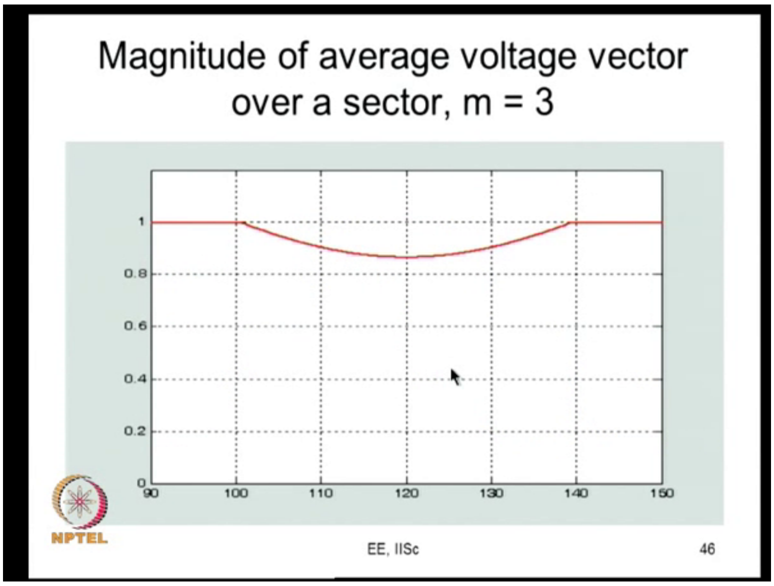

So, this can be clearly seen here. If this is only sector 1, this corresponds to start of sector 1 where R phase is going to the positive peak. So, from one to here it you are not a little more than 10 degrees vector 1 is applied. The last 11 degrees or so, vector 2 is applied the same story in sector 2. Sector 2 in this portion active vector 2 will be applied here is active vector 3, will be applied and so on.

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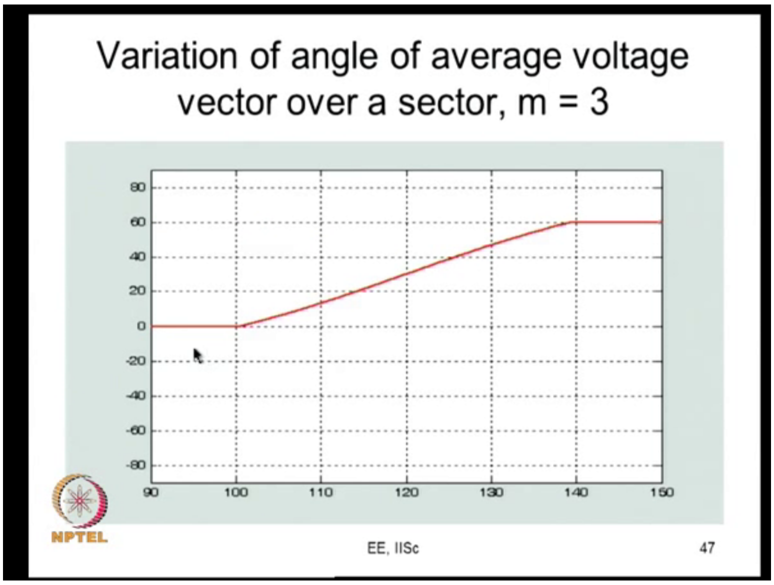

So, what happens to your angle? This since only active vector 1 is applied, for up to little more than 10 degrees, the angle is 0. Again, for the last 10 or 11 degrees, in this sector the angle is equal 60 degree, it is constant. In between it rises; obviously, this is faster than the fundamental angular velocity.

If you look at the fundamental angular velocity it will actually the fundamental average voltage vector, will actually be going like this. But when you when you are looking at the average voltage vector; that is your looking at the voltage vector averaged over every sub cycle, that vector really moves like this. So, you can actually approximate it by a piecewise linear function, 0 here and rises at some velocity here, and I mean with some slope here, and again constant here.

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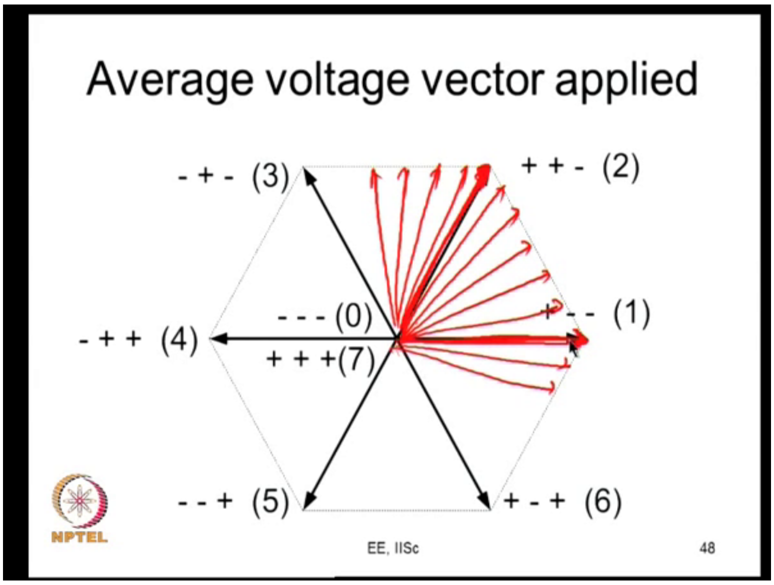

You can approximate it with piecewise linear thing.

So, what really happens here is, you have active vector 1 is applied in one sub cycle. This is repeats in a number of sub cycles you would have applied active vector 1 only. Then you will apply some vectors like this. The vector will go on changing. Again, you will go to active vector 2, and for certain duration you will continue to apply active vector 2. Then it goes in here. This is how the average voltage vectors are in different sub cycles.

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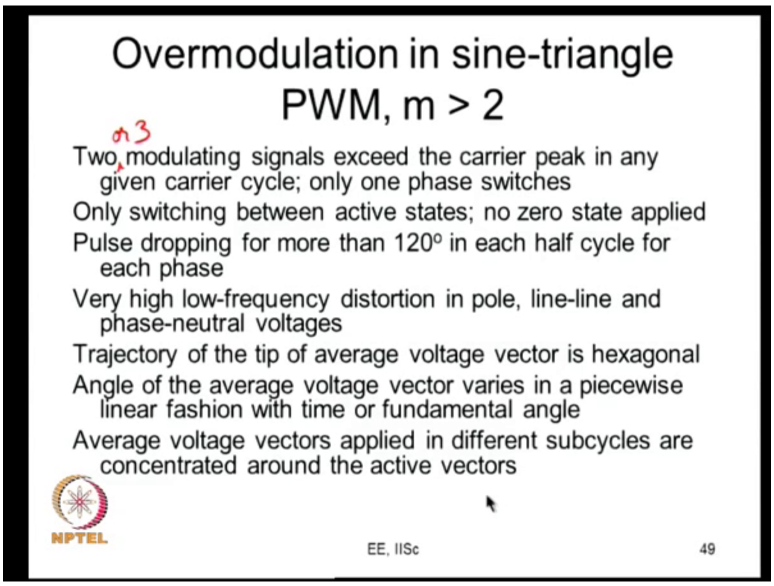

So, if you look at here, what you get is 2 modulating signal exceed the carrier peak and you know for m greater than 2 everywhere. And sometimes only one sometimes even all 3 would exceed that to minimum, and you know sometimes it could be even 3. Which is what you have to make sure here. So, I will probably indicate that here itself, right.

So, this is whenever there is a switching that switching is between active states. And no 0 state is ever applied. And pulse dropping is for more than 120 degrees and distortion is very high, the trajectory of the tip of vector is hexagonal. It is always on the hexagonal. The angle of the average voltage vector varies in a piecewise linear fashion with time. And this is important, because actually these in the space vector domain this is the understanding we will use in coming up with an algorithm for a space vector modulated inverter. And what you also find is the average voltage vector are applied in different sub cycles are kind of concentrated around the active vectors. What I mean is; if you look at this you see that there are many here.

So, you will have voltage vector here, but you have lot of vectors, in in this particular case you have many vectors actually along active vector 1 itself. So, eventually what happens is the depth of modulation goes on increasing more and more vectors will start coming close to this. And will be aligned along with active vector 1. Again, among these vector, more and more of these vectors will get aliened along active vector 2. And finally, when you reach the so called 6 step more, you would have all the vectors in the in the first 30 degree of this sector applied along here only.

And the next to 30 degree you would have all the vectors applied here only. And again first 30 degree in sector 2 all the vectors average voltage vectors will be aliened active vector 2, and so on and so forth. So, this will come closer and more and more vectors will come and merge with this active vector 1 as modulation depth increases.

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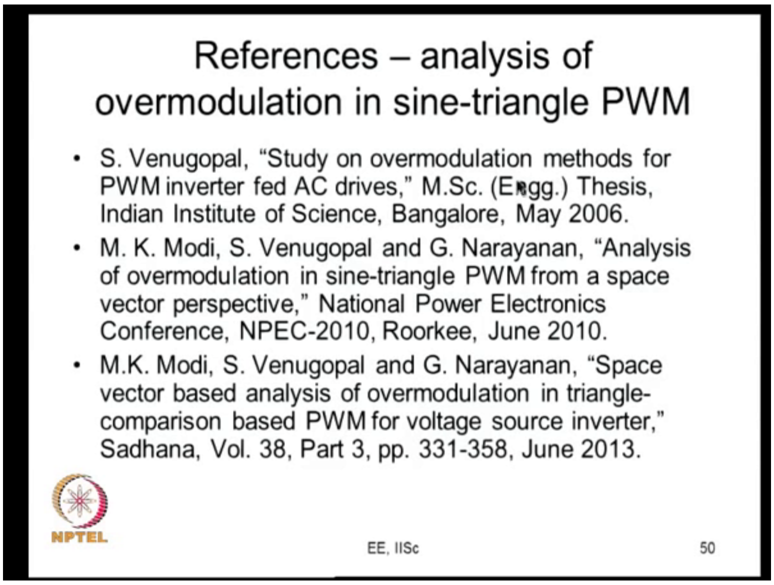

So, you can actually find these details, this analysis of the sin triangle PWM, from a space vector point of view. What happens to the average voltage how does it vary, in this masters thesis about a chat I think a chapter of the thesis covers this. And this was also presented in a I mean a part of this was presented in a conference paper. And this is a more full length general version, in which you will find for sine triangle PWM, and also you will find for the common mode injection PWM now.

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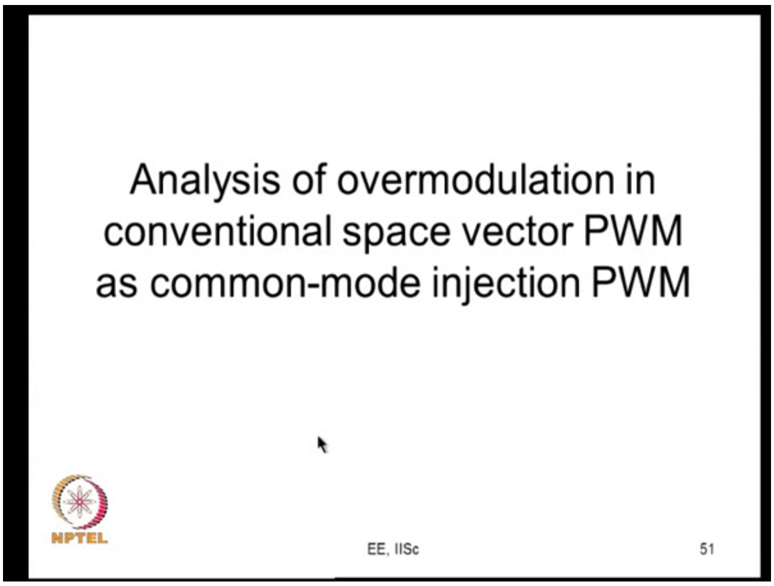

So, let us look at if analysis of the overmodulation in this CSVPWM is pretty similar to that, you know of sin triangle PWM.

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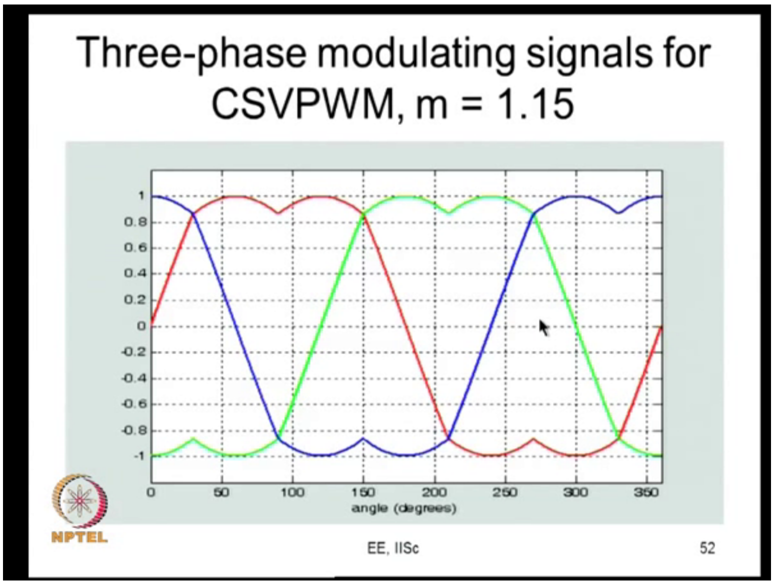

We are looking at it as a common mode injection PWM. So, when you are looking at so called m is equal to 1.152 by root 3, you see that the m R star is just touching 1 which is the peak carried, it is not going above that, it is not going below. So, you are into linear modulation. So, there is no problem. So, you have your average m you know these are the 3 phase voltages, the average pole voltages.

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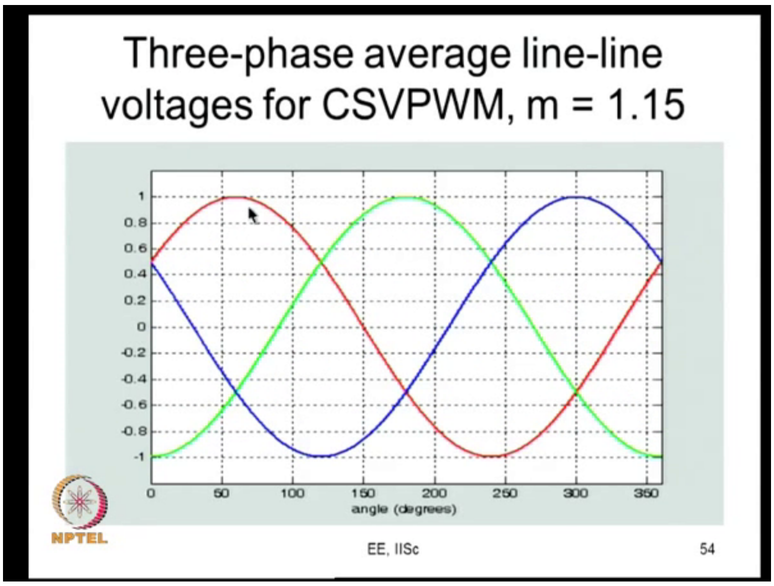

And you look at the line to line voltages, the line to line voltages is the average voltage just touches V DC; which is equal to V d 1. One stands for V dc. So, you have nice sinusoidal voltages.

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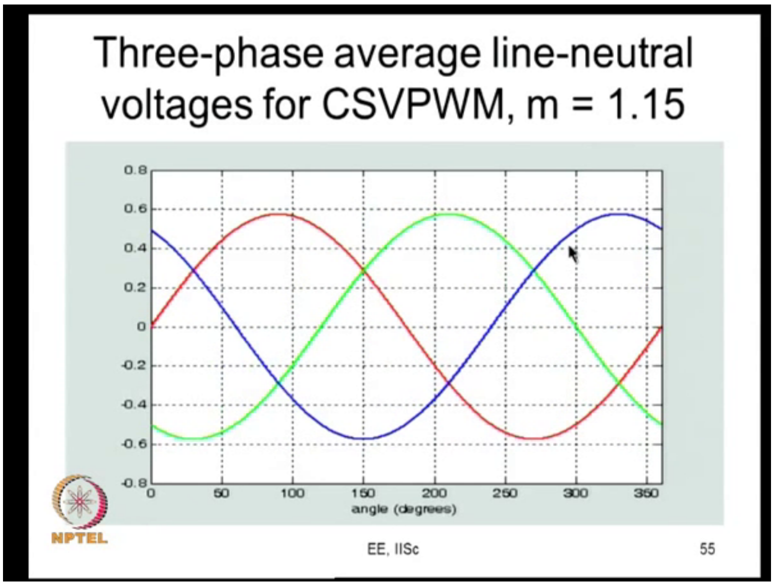

And the line to neutral voltage is on the load. V RN averages V ON average and V BN average are also nice sinusoidal wave forms, and incidentally this peak value is what? It is 0.577 that is 1 upon root 3.

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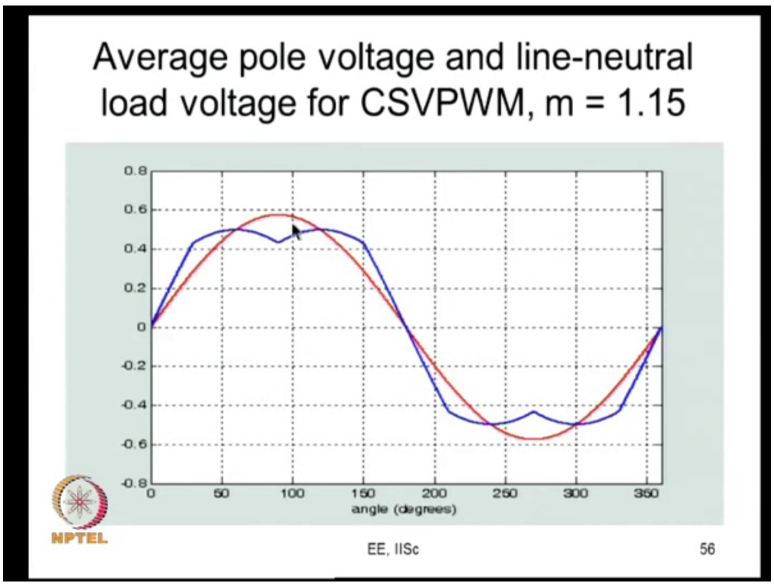

Now, what you have here is this, this V RO average it has a peak value of 0.5 V DC, and this is 0.577 V DC. Again, you know at the kai expenses of repetition, I would say that whatever triplen components are here you subtract them you are actually getting this now. So, you are able to pack a higher fundamental voltage of 0.577 V DC into a modulating signal whose peak does not exceed 0.5 V DC. That is what you are achieving now.

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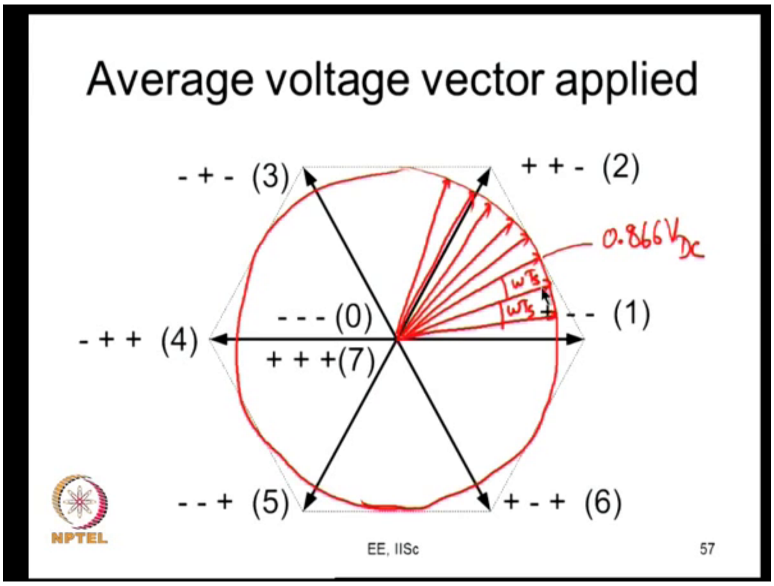

So, here what happens? You are looking at the average pole voltage. So, if you look at what are the different average vectors which actually produced, what you will find is; you will find their tips to follow a circle like this. Their tips will actually be following at this modulation index. You do the analysis as we did for sin triangle PWM before. So, what you will find is, you will find that sub cycle by sub cycle you will get an average voltage vector whose magnitude is constant, and it will vary like this.

So, this magnitude is equal to 0.866 V DC. For our convention and this angle is omega T s, the angle between average vectors of any 2 consecutive cycles is omega T s. This is the situation when you have conventional phase vector PWM, and it is modulation signal m is equal to 1.15. So, I mean that is the thing.

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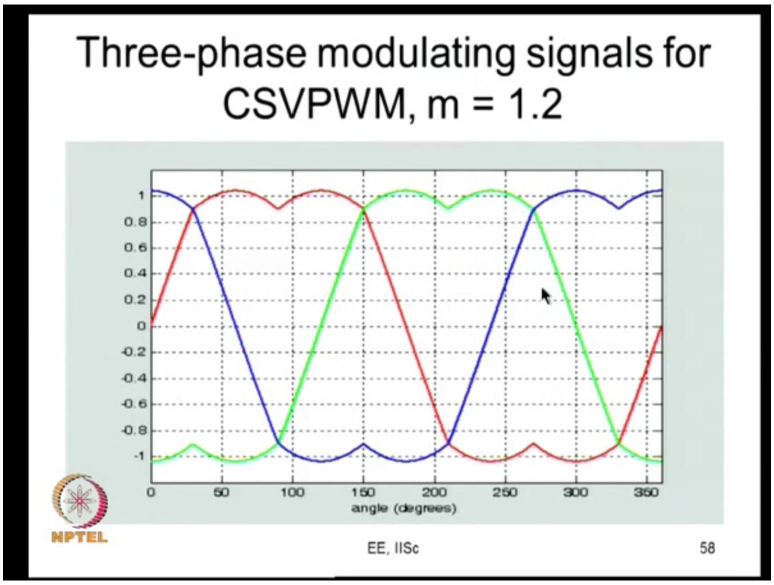

Now, we go above that. From 1.15 we go to 1.2. So, we see that for small region, the CSVPWM modulating signal goes above that, here it go. Once again here it goes above the peak. In sin triangle PWM you would have found that it went above, the mean the only here, but here it goes above here and also here. That is around 60 degree and also around 120 degree. The same way look at negative half cycle, R phase modulating signal is going below, the peak here the negative carrier peak, here also it is going below the negative carrier peak.

So, in these are regions where you are going to clamping for R phases, similarly for the other phases now.

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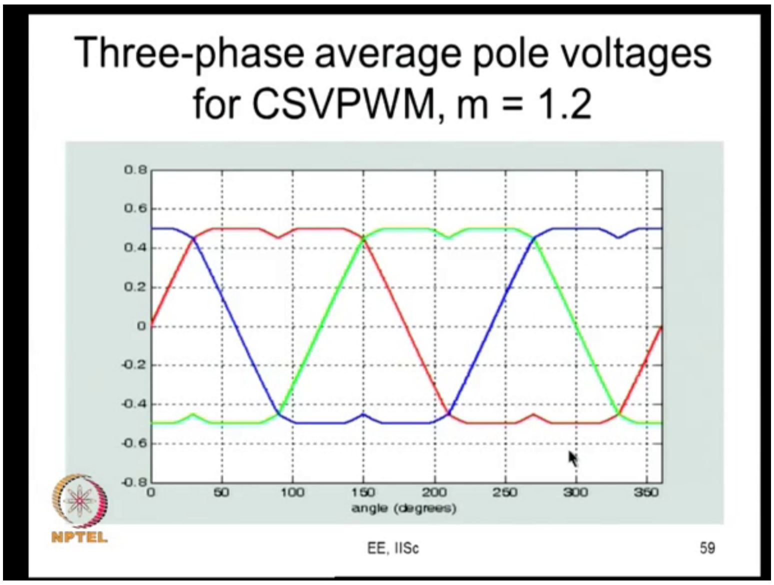

And that is what happens this is pulse dropping. There are no pulses while there are pulses here the R phase switches here, it does not switch here. The pulses are would be missing. So, it is called pulse dropping your pulse dropping here and here, and also here and here, for all the phases now.

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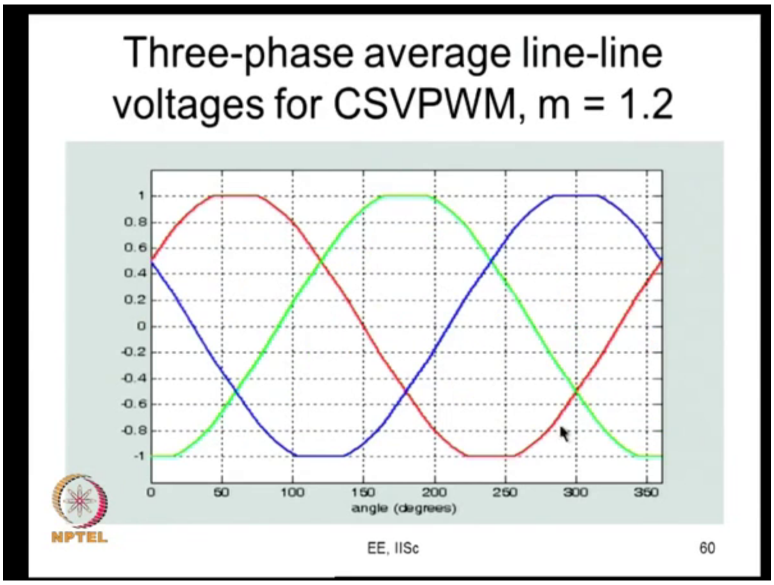

So, the same kind of analysis is still valid. You if you calculate V RY average it will look like this. Now you can see that V RY average is equal to V DC. V RO average cannot exceed V DC by 2, V RY average cannot average exceed V DC, why? Because V RY the instantaneous value the maximum value is only V DC. If you apply V DC throughout the sub cycle you are going to get plus V DC. Similarly, V RY average can also not go below minus V DC, because if it is minus V DC is applied throughout the sub cycle is you get minus V DC. You cannot get anything lower than this, you cannot get anything higher than this.

So, you see your V RO, V RY average is clipped like this. And you can see there is a significant amount of distortion here.

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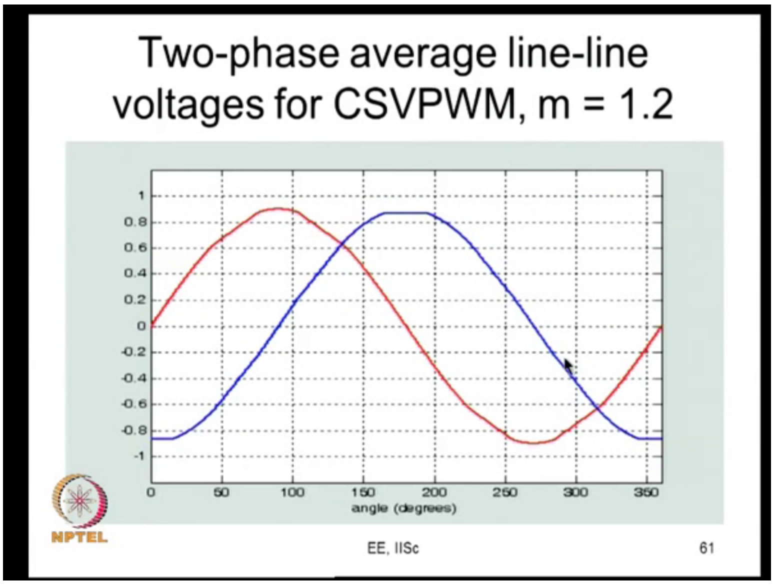

Now, you go into V RN average, you do not see any clipping here. Because that the triplen frequency components have all been subtracted and all that. So, on, but you see that it is goes well higher, you can see that it goes well higher. This this is V alpha average and V beta average, of course. So, you know it has a tendency to go closer to 1. It will reach somewhere close to 1. You take it 0 here, at the same time it is 0 V beta average is 0 and this value something like 0.9. So, the vector is something like 0.9. So, you would you are actually approaching 1.

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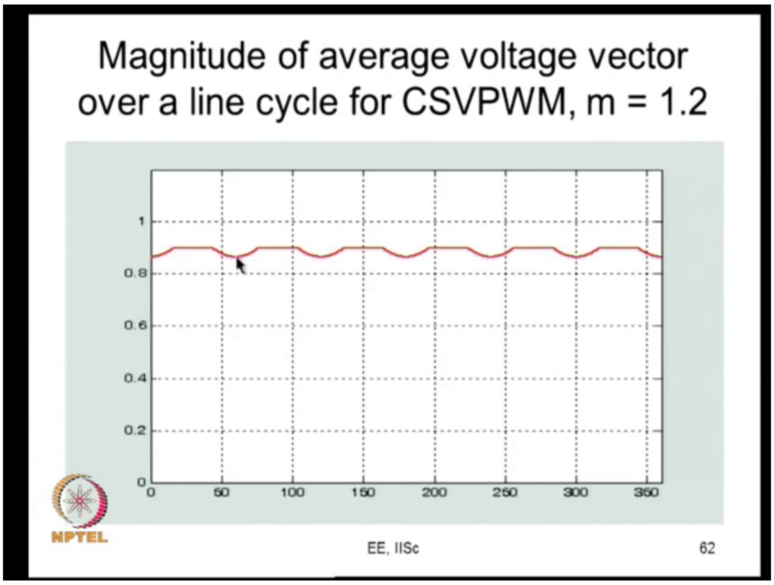

So, if you look at the vector, the magnitude of the average voltage vector, it is constant and then it varies. It is constant and it varies. It is constant it varies. So, it has the periodicity of 60 degree every sector, will x talk over sector 1. It is start from 90 degree were R phases first to peak, that ends with 150 degree where B phases as negative peak. So, initially you find that it is constant. That is active vector 1 is applied here, active vector 2 is actually applied. So, that is what happens now.

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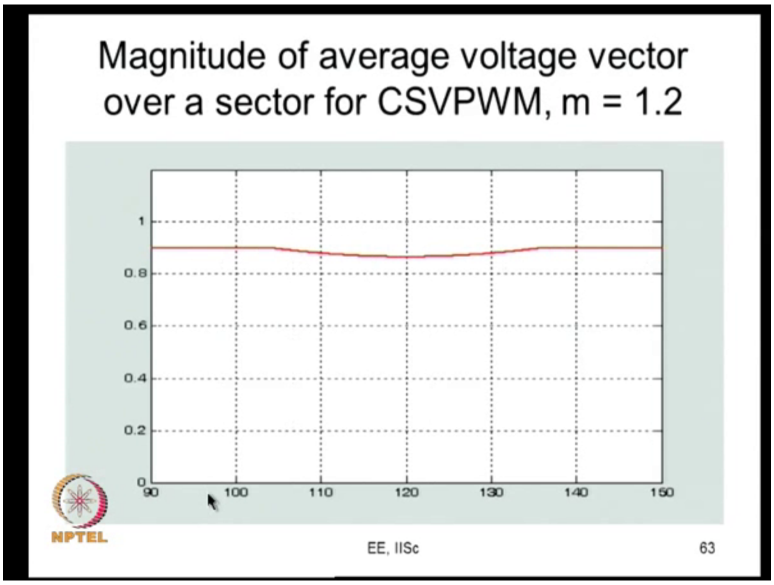

So now if you look at I have only 1, sector you can see that more clearly. Here it is active vector 1 applied, active vector 2 applied, then here there is switching some between active vector 1 and active vector 2, and the magnitude varies like this now.

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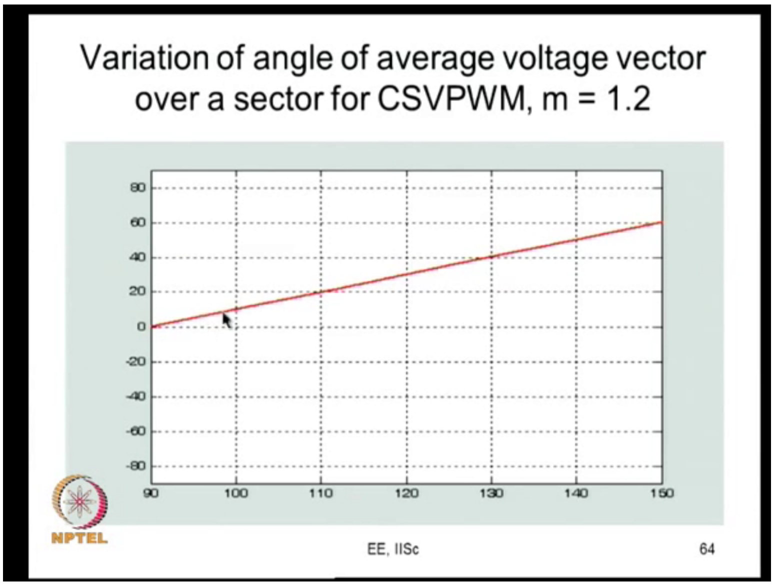

So, if you look at be fundamental angle, I mean the angle of the average voltage vector, it is same as the fundamental angle. It just rises linearly. So, the angle velocity continues to be constant now.

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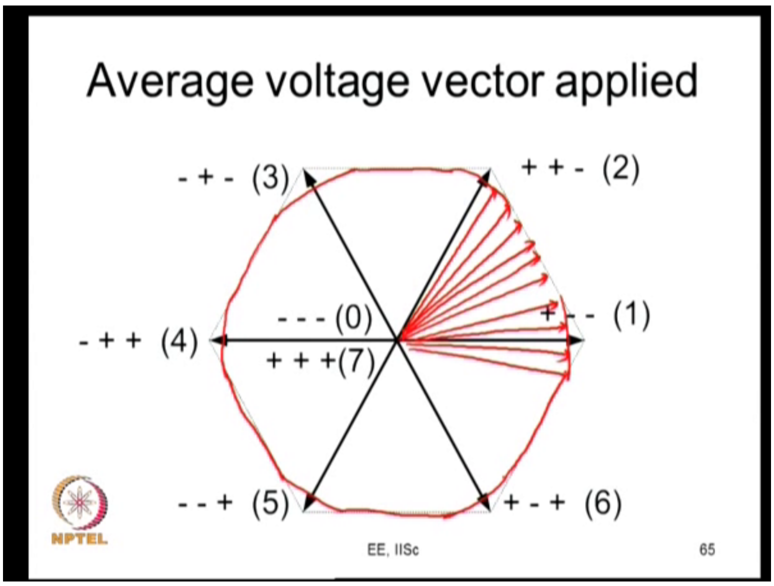

So, what do you get here? So, you would have some places, where you know we are looking at some modulation index of 1.2. What you will find is; you will find that there are some places where you may have some vector applied, and in there are some other places where you may have you may find some vectors applied like this. If you go back you will see that there are some place, here for example, here only one phase which has have take here. Only Y phase switches whereas, B RN and B are clamped.

So, this is the case where only the active vector switching, and in this case, there is no 0-vector applied. And the average vector tip will be touching the hexogen. Whereas, you take here, R phase switching, Y phase is also switching, and B phase is also switching. So, these are places where all the 3 phases are switching. And therefore, the 0 state is also getting applied. Though to lower you know though the duration of application of 0 state would be lower now than it was during linear modulation.

So, here you find all the 3 are applied. During this time what happens? It actually follows the circular projection of the trajectory. What happens here is this follows a circular portion. In this part it goes like that like this. So, once again what you will have here is, you have it like this. So, the trajectory is partly on the hexogen, and it is partly on the circle. It is partly on the hexogen, it is partly on a circle, this is how the trajectory looks for you. This is how the trajectory looks ok.

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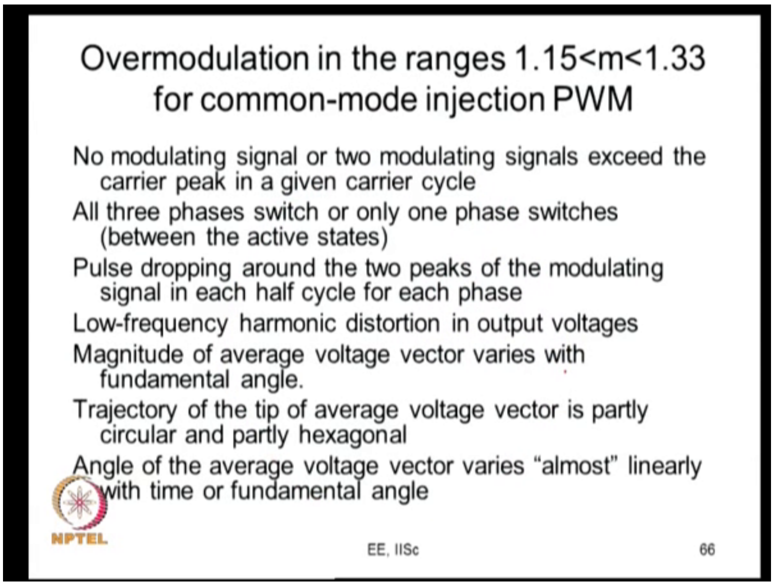

Let us go further. This is something we are trying to something summarised. That there is no modulating signal or 2 modulating signals exceed the carrier peak in a given carrier cycle. So, if you know if know modulating signal exceeds all 3 phases switch, and you are on the circular portion of the trajectory. Otherwise only one phase switches and that is the switch is between the active state and you are on the hexagonal portion of the trajectory. You can see pulse dropping around the 2 peaks of that and a then there is a lot of low frequency harmonic distortion, and you can see the magnitude of average voltage varies with fundamental angle. The trajectory is partly circular partly hexagonal and the angle of average voltage vector varies almost linearly, with time or fundamental voltage.

So, you can see that there is some similarity and dissimilarity here. In the case of sin triangle PWM, we found the voltage was varying when you went into the overmodulation, but it was not really you know the magnitude is varying here also the magnitude is varying. But there is a clearer pattern in the magnitude variation here it is circular hexagonal circular hexagonal it is falling the trajectory like that the next one. So, there is some similarity there is some dissimilarity. Again, when you are into overmodulation sin triangle PWM, you know upto some extent that is when you have not gone close 6 step operation, you are movement of this is linearly with time mean the angle where is linear with time the angular velocity is almost constant, which is also true here for conventional space vector PWM.

So, this was non circular here, in sin triangle PWM here; if have it as a partly circular partly hexagonal. In this case there is similarity, you see that it is it is almost linearly with time angle varies almost linearly with time angle. So, you see that there is a great amount of similarity here. So, initially during overmodulation, what happens only the magnitude of the vectors starts varying. The angular velocity continues to remain uniform.

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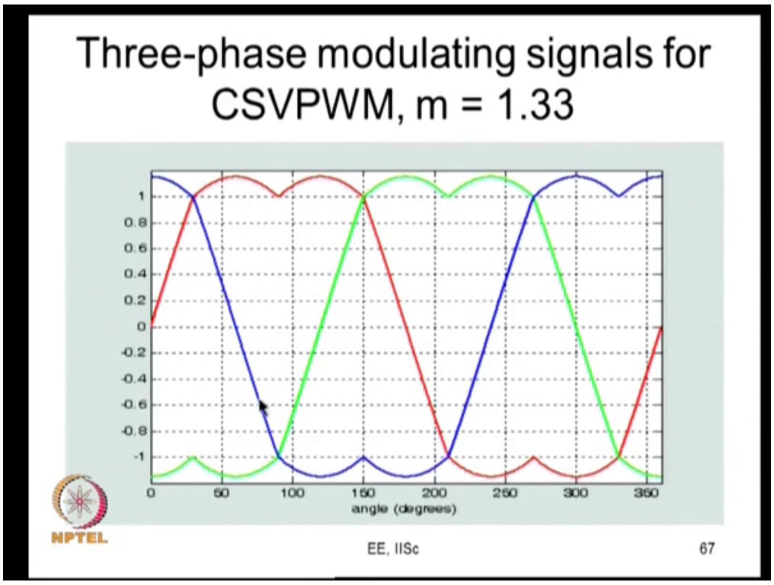

But then that will soon change now. When you touch m is equal to 1.33 with CSVPWM what you find is for an entire 100, 120 degrees you are above the peak of the carrier. And therefore, the phases clamped for 120 degrees here and it is for clamped 120 degrees here.

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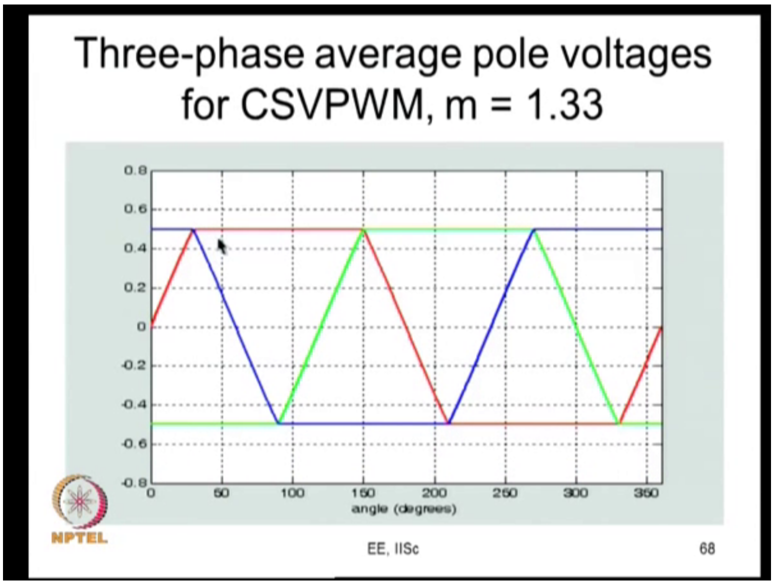

So, you have 3 phase pole voltage like this. So, this is similar to what we had for m is equal to 2 for sine triangle PWM. The same average pole voltage we got for m is equal to 2, at m is equal to 2 you will have a very similar kind of may be only a small difference will be there in this 1. That would have been the sinusoidal wave there is some sin with some common mode added here.

So, you will have add a very similar average pole voltage when you considered m is equal to 2 for sin triangle PWM. So, this is how the average pole voltage looks roughly trapezoidal.

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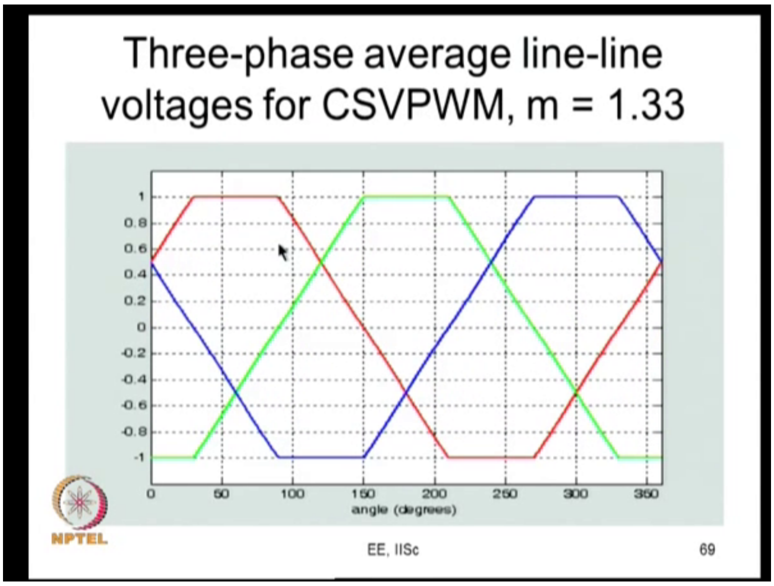

And this how the line to line voltages will be they also look trapezoidal the duration of the clamping is lower.

So, here this means basically R and Y are both clamped concurrently here. This means that Y and B, I mean Y and B are both concurrently clamped here. This means both B and R are concurrently clamped in this interval.

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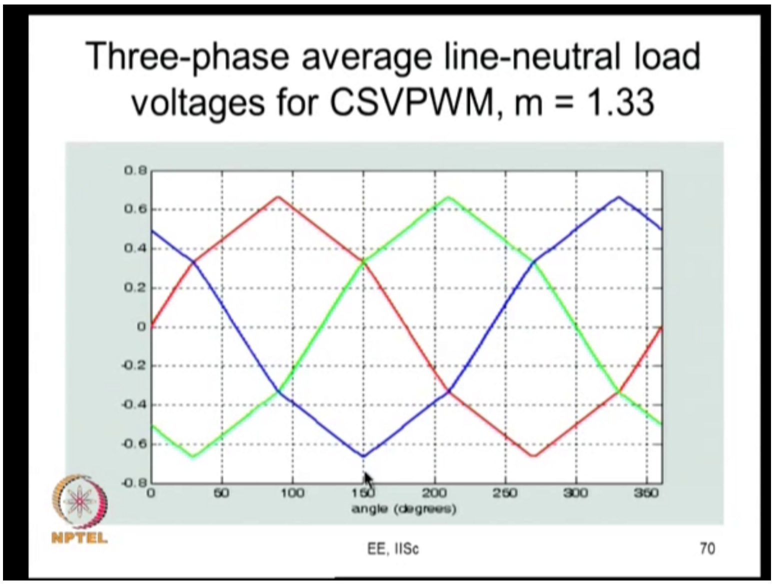

So, if you look at that you can see these are the hexagonal waveforms. This is V alpha average and V beta average. So, the 2 components of the average voltage vector, in this stationary reference frame is V alpha average in this is V beta average at 1.33.

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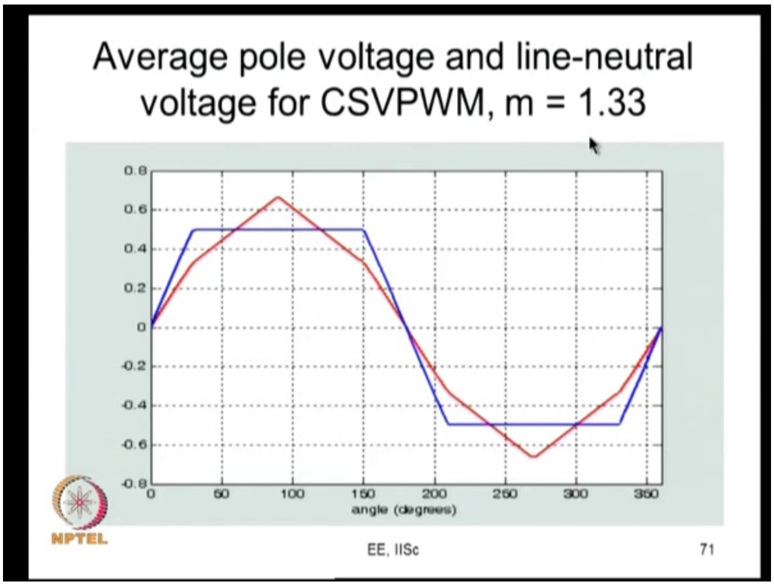

So, this V R average, and this is V RN average to emphasis the point. So, very similar to what is was is at m equal to 2 with sine triangle PWM.

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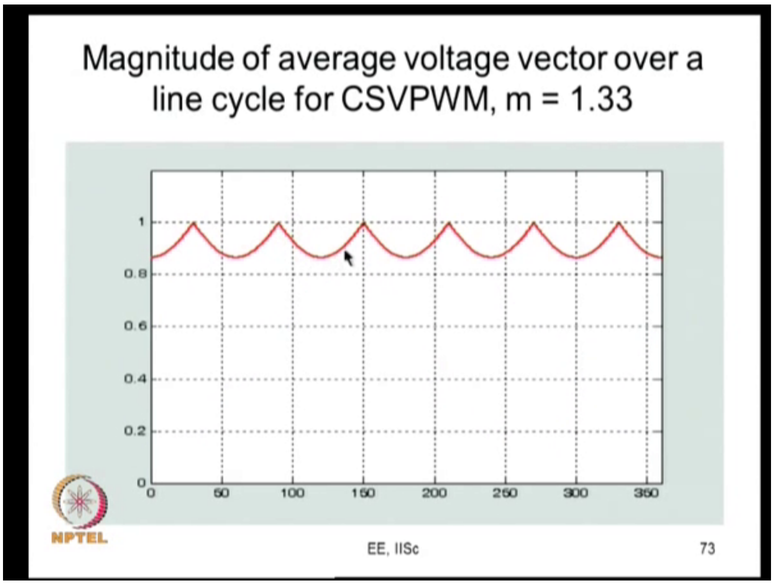

So, now what I am going to do? Look at the voltage vectors they vary like this, over every sector.

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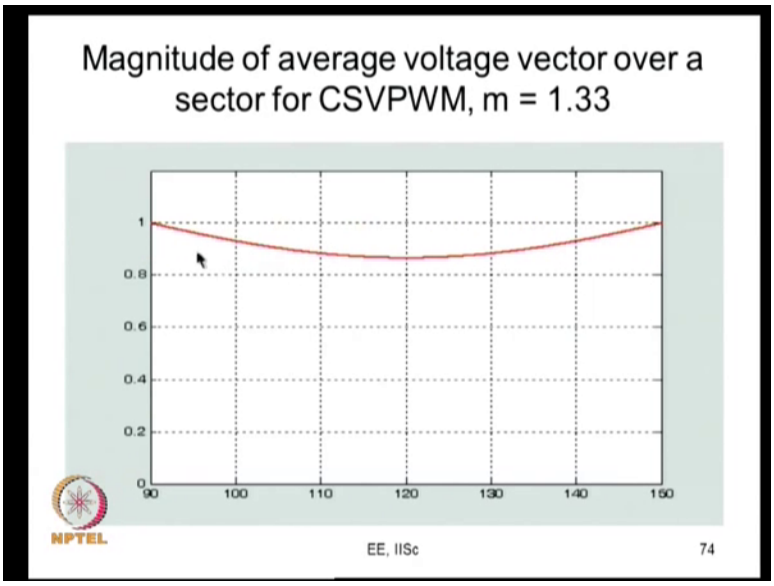

If you look at the variation over only one sector, if the variation is like this.

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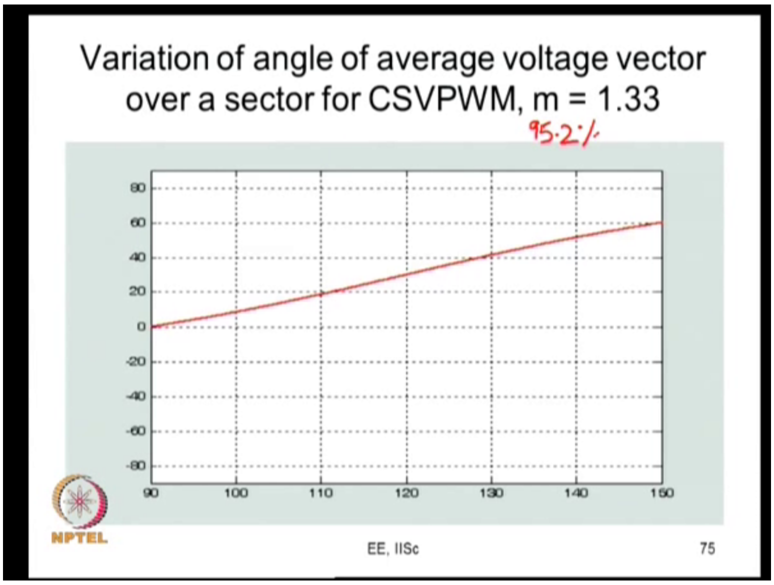

And if you look at the angle, the angle is still linear. This happens upto 1.33 it happened up to m is equal to 2, in both cases what you should remember is the fundamental voltage is similar how much is the fundamental voltage the fundamental voltage is 95.2 percent of this 6-step voltage say 95.2 percent of this 6-step voltage.

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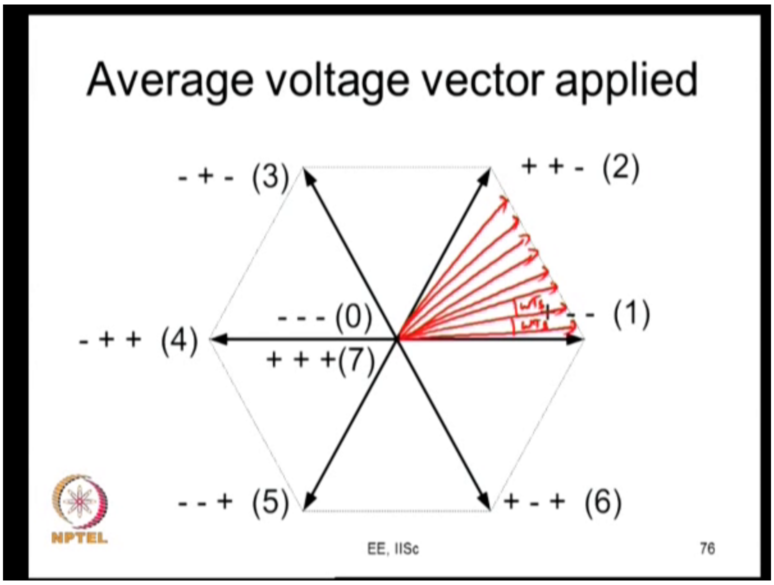

So, if you look at this what happens? The average voltage vector would touch the tip. Next sub cycle all side touch the tip, next sub cycle also the touch tip.

So, it will be like this. This is how the average voltage vector will be. So, how about the angles all the angles will be equal? These angles will be omega T s, but when you go above that 1.33, you will start seeing that this. Average vol I mean angular velocity will start changing.

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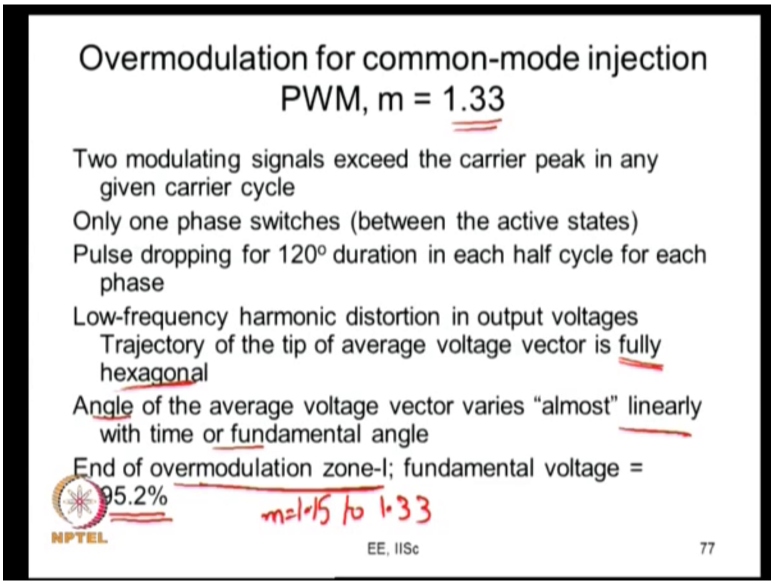

So, let us as I mentioned to you. This is 95.2 percent, and we called this as overmodulation zone 1. In this space vector modulated inverter. That is in this case what will happen is, the average voltage the angle would vary almost linearly with time, whereas the magnitude will change. How will the magnitude change?

So, it will be you know in overmodulation zone 1 it will be partly hexagon and partly circular. And at m is equal to 1.33 this becomes fully hexagonal. So, up to this m is equal to 1.33, some 1.15 to 1.33 we would call as overmodulation zone 1. That is from 1.15 to 1.33, these are the values of m you would called this.

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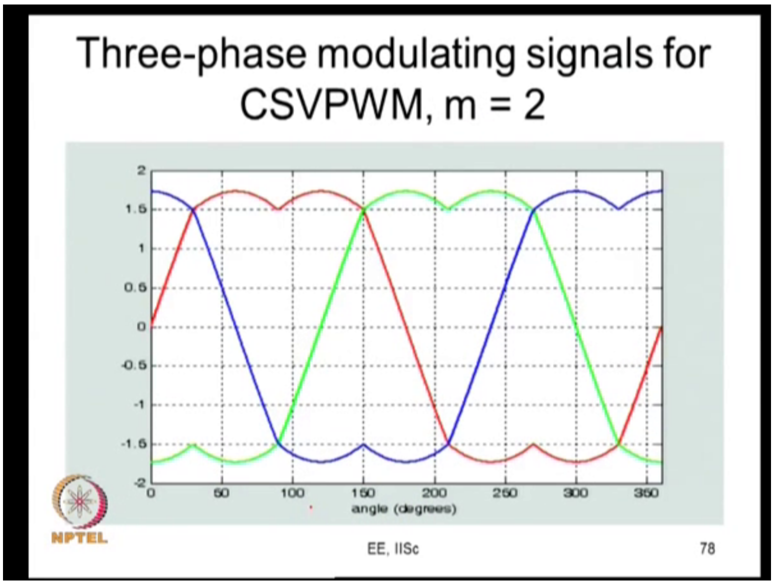

Above that you will call as overmodulation zone 2.

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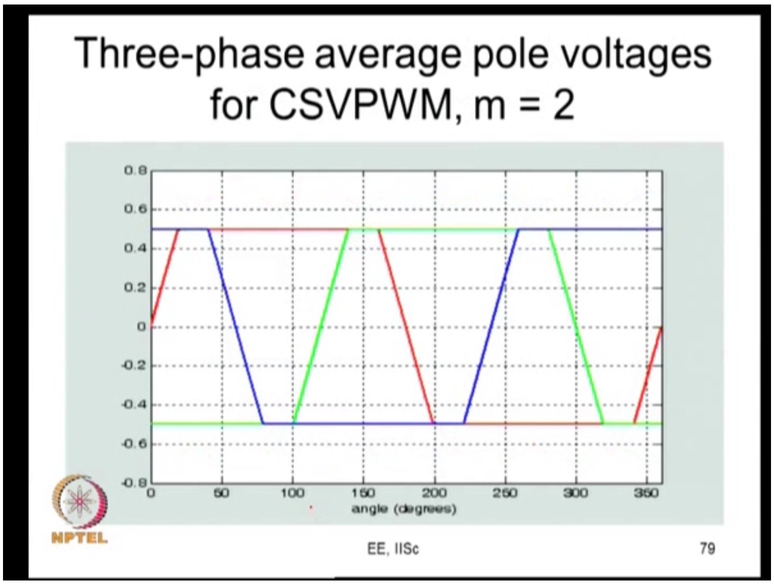

So now this is an example for m is equal to 2. You can see that this angle is quite long, much longer than 150 degree now.

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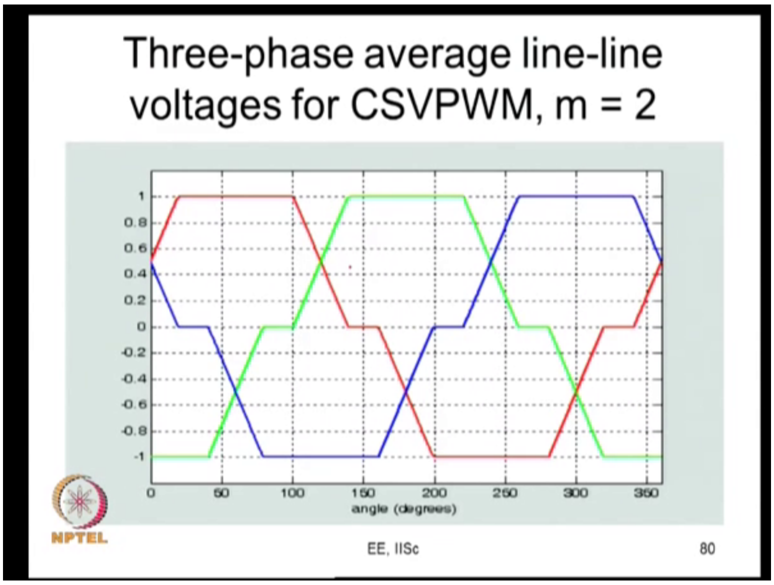

So, if you look at this is your average line to line voltage. So, V RY is fixed to plus V DC for a long time, the same thing about V YB.

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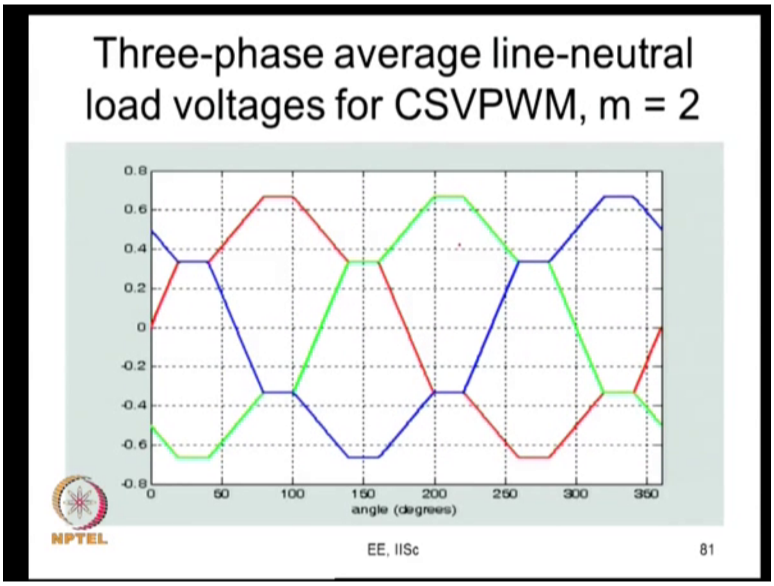

So now if you look at it here this is V RN average and this is V YN average. So, V RN average is also not changing, I mean this is V BN average is also not changing.

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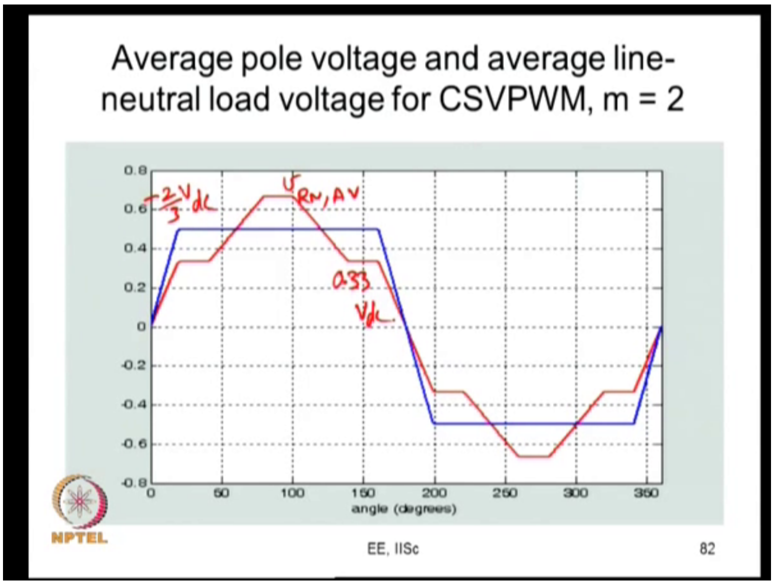

So, this is your V RO average, and this is your V RN average. And you can see that the V RN average is here this is 2 by 3 or 0.67, this is 2 by 3 V DC. This will be 0.33 V DC.

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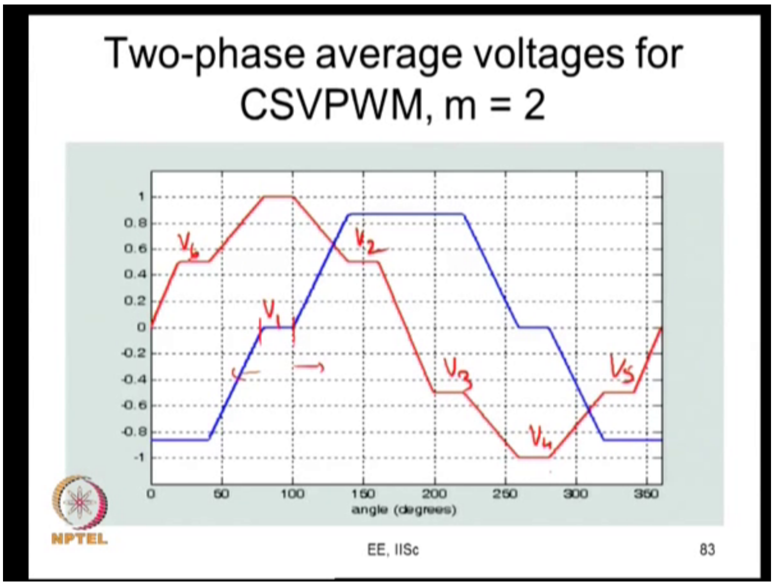

So, you get wave forms like this, and you will see here, V alpha is equal to 1 V beta is equal to 0. So, this is a vector voltage vector 1 is applied here. And here you will find voltage vector 2 is applied, here voltage vector 3 is applied. The here voltage vector 4 is applied here voltage 5 is applied throughout. What happens is gradually this expands, the time for which is expand and it goes on increasing.

Finally, only the active vectors are applied V 1 applied for 60 degrees, V 2 of 60 degrees, V 3 of 60 V 4 and V 5 and once the finally, V 6 is applied.

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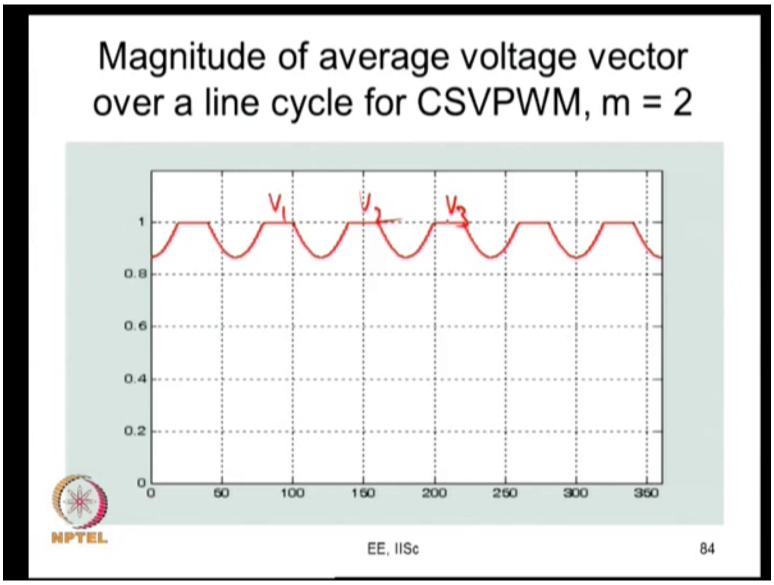

That would what would be your 6-step mode. So, we are little ahead of 6 step mode. So, here as I told is vector V 1 vector V 2 vector V 3 are all applied here.

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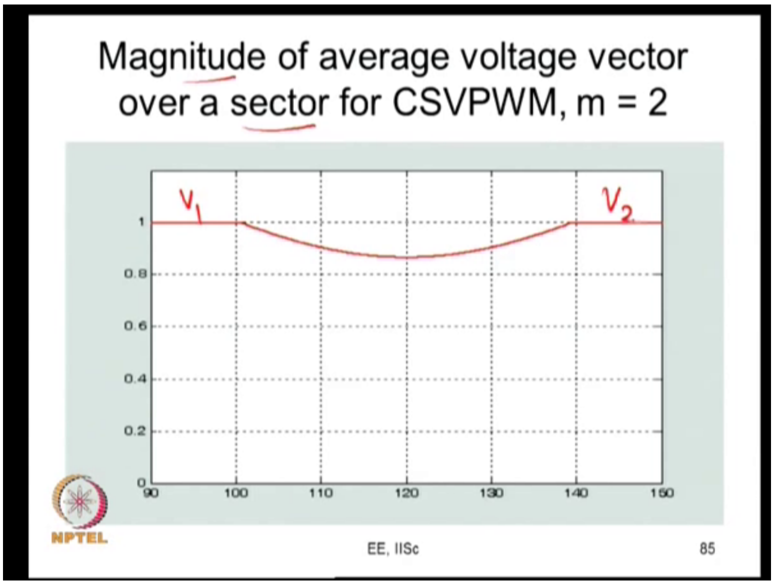

So now this is how the magnitude varies over a sector. So, initially the same vector 1 is applied here. This is active vector 2 is getting applied.

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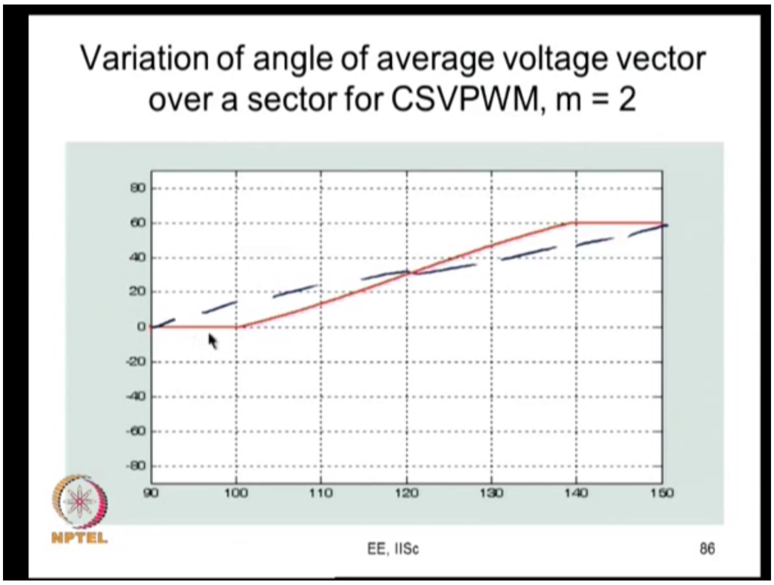

So, the angle varies somewhat in a piecewise linear fashion this is 0, this is 0, and it moves with some slope and this slope is certainly higher than the slope if you join these 2 lines by straight line. So, this angular velocity is higher than the fundamental angular frequency. So, over all you know whatever time the fundamental angular frequency would take. For example, if there is this fundamental o vector that will move like this. At a uniform velocity now, the applied voltage vector is initially little slow, and then it is much faster and finally, it is slows down this is how it happens now.

So, you have your vectors, how do you get them? In this region you have the active vector being applied.

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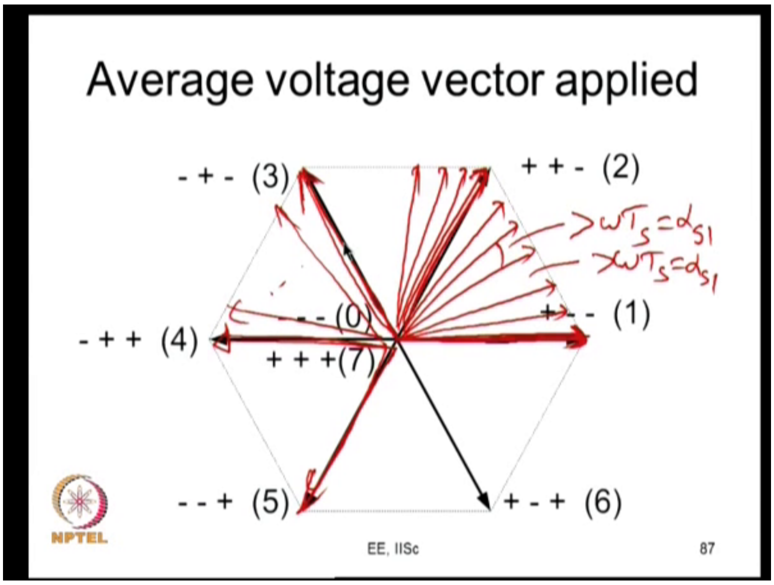

So, like we did before for sine triangle PWM, what you will have is; you will have let me change it to red. So, in sub cycles surrounding here, the same active vector the you know the average vector is equal to active vector 1. Then it goes around the sub sequence sub cycle it goes out. And this angle is greater than your omega T s, this angle is greater than your omega T s, this is also greater than your omega T s.

So, let us call this as some alpha s 1. This is also that alpha s 1. So, again when you got active vector 2 it is applied continuously like this. And then in the next sub cycles will have vectors like that. When you come closer to active vector 3 again for the number of sub cycles the average vector applied over the sub cycle will be equal to this now. So, you will have you will have many vectors applied here. And a few vectors in between. In few of the sub cycle, as time goes on as the depth of the modulation goes on increasing, you will have more and more of these vectors getting aligned here. And that would be 6 step operation now.

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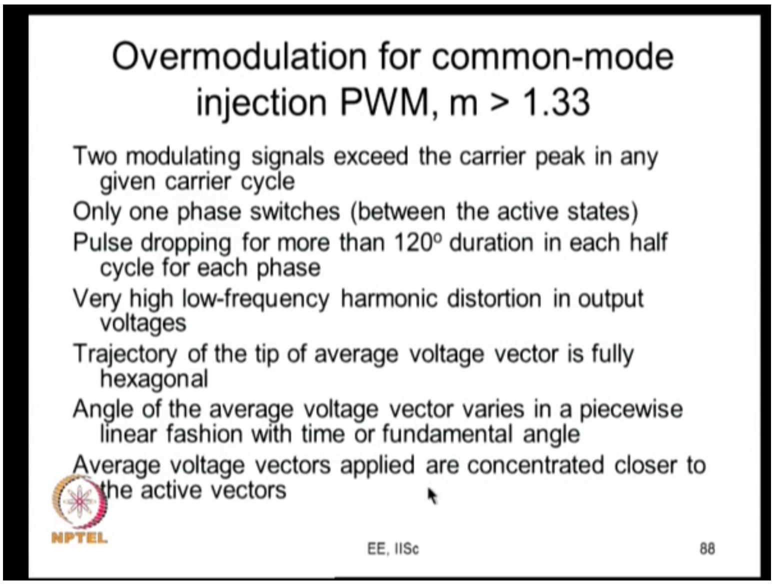

So, here I would just try to summarise that. So, it is it is pretty similar to what it was in sin triangle PWM when you look at m greater than 2. The same story here when you have m greater than 1.33 ok

So, the trajectory of the tip of the vector fully hexagonal, the angle varies in a piecewise linear fashion, and the average voltage vectors are concentrated closed I mean basically many of the average voltage vector are along the active vector. That is what is the more precise statement than saying.

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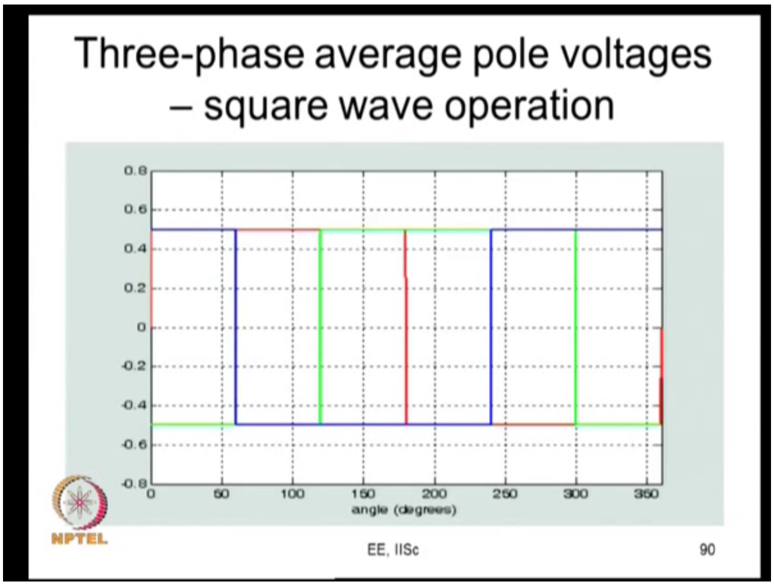

So now what we can do is if you look at the square wave operation that is at the end. So, every phase is switching R phase is switching here at after 180 degree. So, Y phase also switches here and after 180 degrees. So, this is square wave operation.

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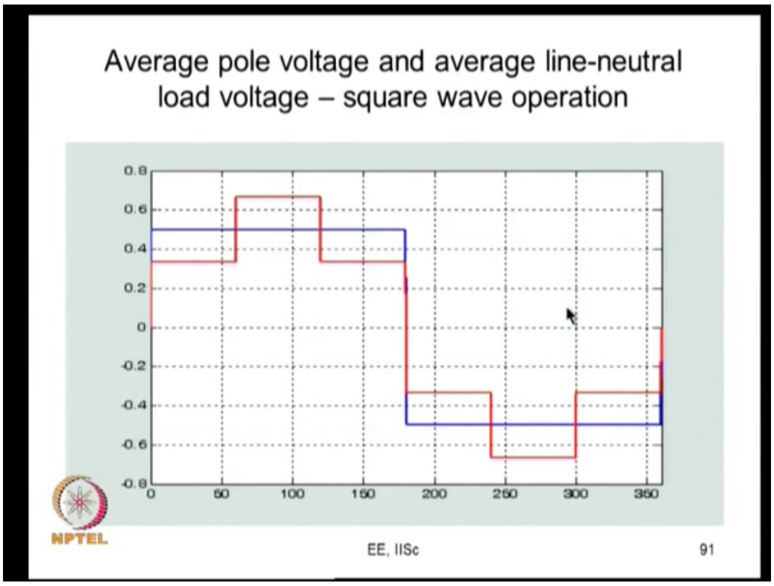

So, your V RO average is a square wave like this. And V RN average would be this there is a third harmonic common mode you will find triplen frequency common mode, you subtract that from V RO average you will get your V RN average like this. And this is V RN average, this is 2 by 3 V DC, this is 1 by 3 V DC, this is minus 1 by 3 V DC, this is minus 2 by 3 V DC. And similarly, you will have V YN average and V BN average, they can be transformed into V alpha average and V beta average.

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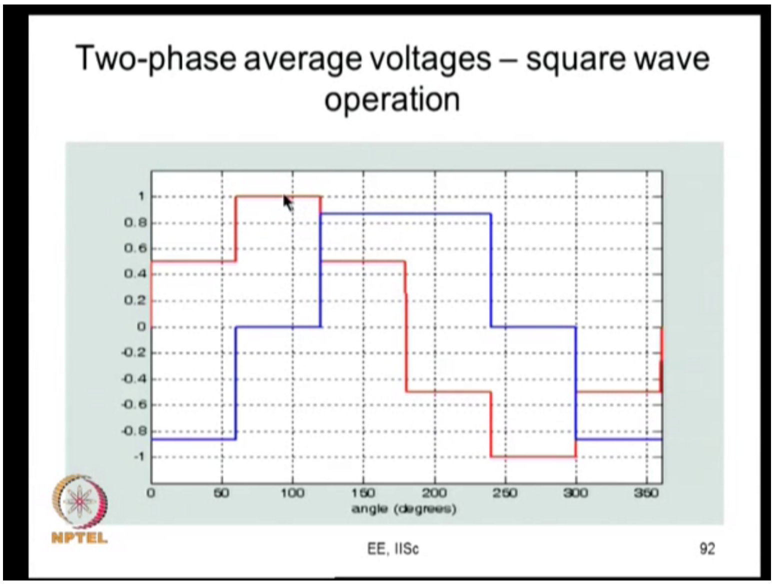

So, V alpha average has a same shape as V RN average, and this is your V beta average.

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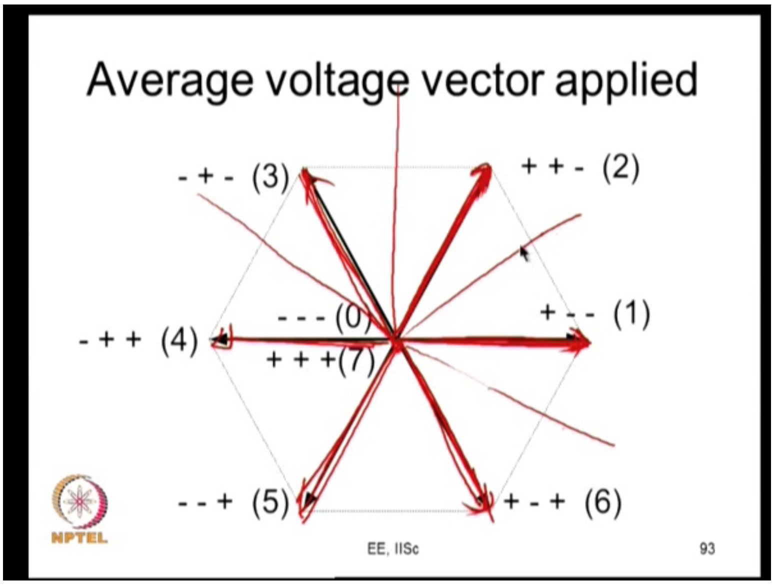

So now what happens? What I told you before, that is for a 60 degree duration, starting from here to here. So, when your fundamental voltage vector moves here to here, all the vectors in every sub cycle are applied like this. Similarly, for a 60-degree interval starting from here to here, all the vectors in every sub cycle the average voltage vector applied is equal to V 2. The same story is repeated over this 60-degree interval. So, it is the same average voltage vector equal to V 3 applied.

So, what you have is, you always have only these vectors getting applied as the average voltage vectors, is only same vector. So, no vector other then this 6 vector ever get applied in any of sub cycles. And in all the sub cycles in this 60 degree this is only vector applied. In all of them within the 60 degree is only vector applied, and this is; what is your 6-step mode this is your square wave operation now.

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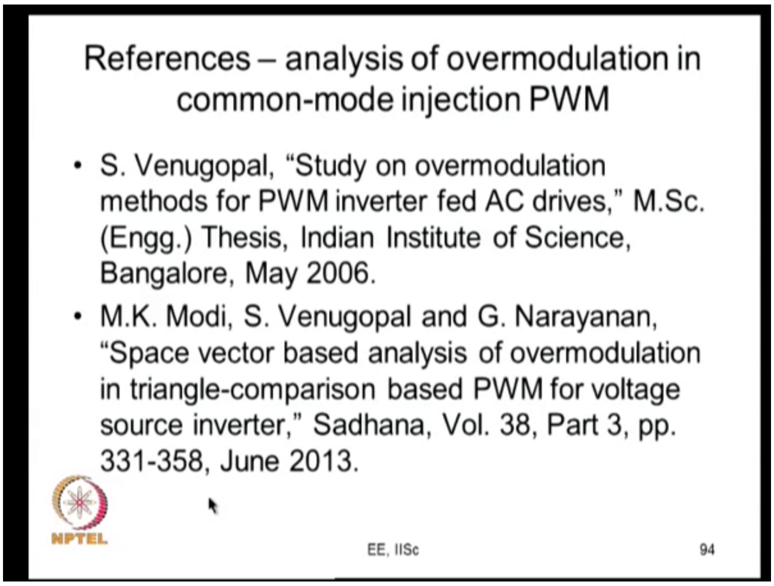

So, you know you can find things from this thesis. The mean this and here this paper in sadhana journal, this talks about the analysis of sin triangle PWM, and also the common mode injection PWM from space vector point of view.

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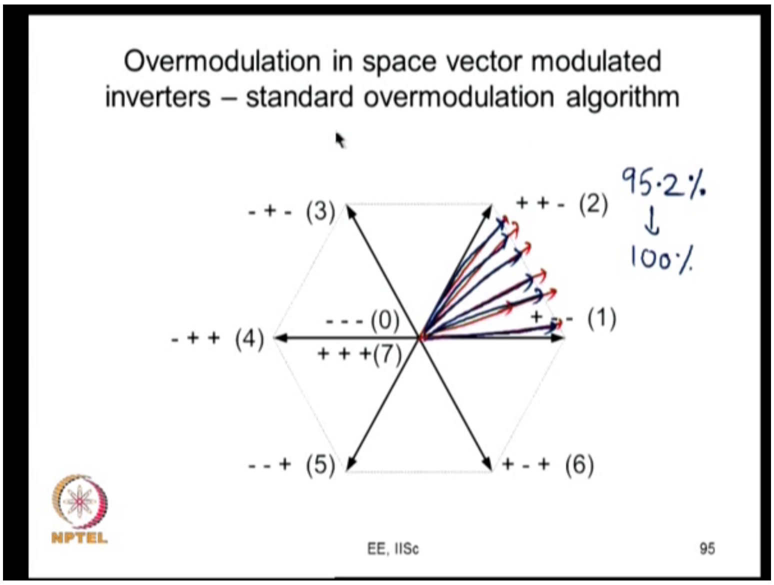

This would be a good reference now. So, if you look at this you know in this space vector modulation, you have a reference vector like this. We have a rotating reference vector like this. So, what do you do? The reference vector goes on increasing. You go about increasing the magnitude of the reference vector. And you know that is what you do to increase your modulation. Can you reach 6 step by simply by increasing this? Probably not.

So, let me say what happens now. You go about increasing this. Let us say, your reference vectors go like this. This is your reference vector. This is your reference vector they are well going outside the hexagon. Can this be realist no they cannot be realist. So, what can be realist? What can realise only this part, what can realise only this part. So, let us say you apply these vectors. Now what is your modulation index? Or what is the fundamental voltage? The fundamental voltage would be only 95.2 percent of this square wave. You but you have to reach 100 percent.

So, when you are when your providing your 3-phase reference when you are providing them a 3-phase modulating signal, you go on increasing you know the modulating signal peak. It goes into you know 6 step operation, but here it does not go automatically into that, you need to do something. What have you got to do? You have to change your reference vector, such that in these sub cycles the reference vectors get shifted closer to the active vector 1, and in these sub cycles it get shifted closer to active vector 2. When you are doing space vector modulation, when you when your references specified as a voltage space vector and so on, you need a special overmodulation algorithm.

Normally, we have what is called as a standard overmodulation algorithm, or which is a 2-zone modulation algorithm.

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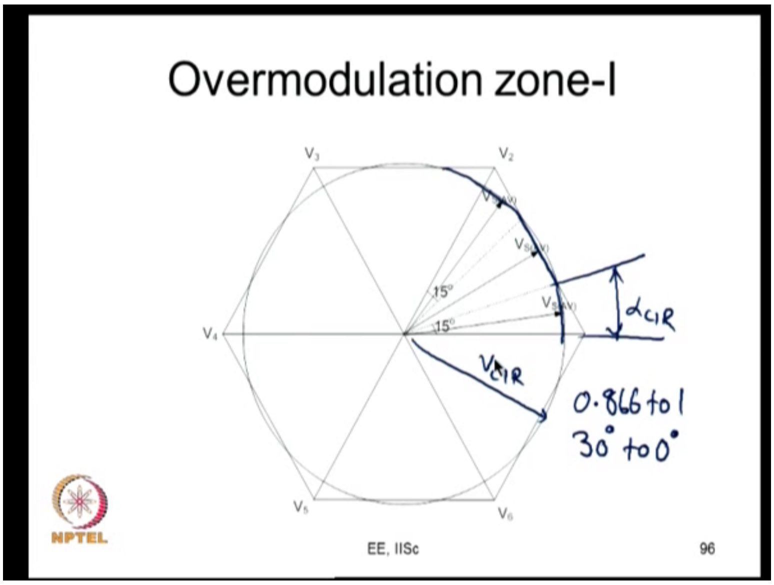

The zone 1 of the overmodulation algorithm can be given like this. You have may have a reference, you know this is partly within the hexagonal partly outside the hexagon. What you would actually do is; you would produce vectors like this, whose tips are like this. You would produce vectors whose tips are like this. This would be called as overmodulation zone 1. And the radius of the circle, we can probably call it as V circle. Or we can call this angle as alpha circle. What you can see is; this V circle can be used to control the fundamental voltage.

So, V circle can vary between 0.866 to one. Or alpha circle can be can vary between 30 degrees to 0 degree. By varying this you can control the fundamental voltage, but there is a non-linear relationship. V circle is not related to fundamental voltage in a linear fashion as be reference was. There is some non-linear relationship.

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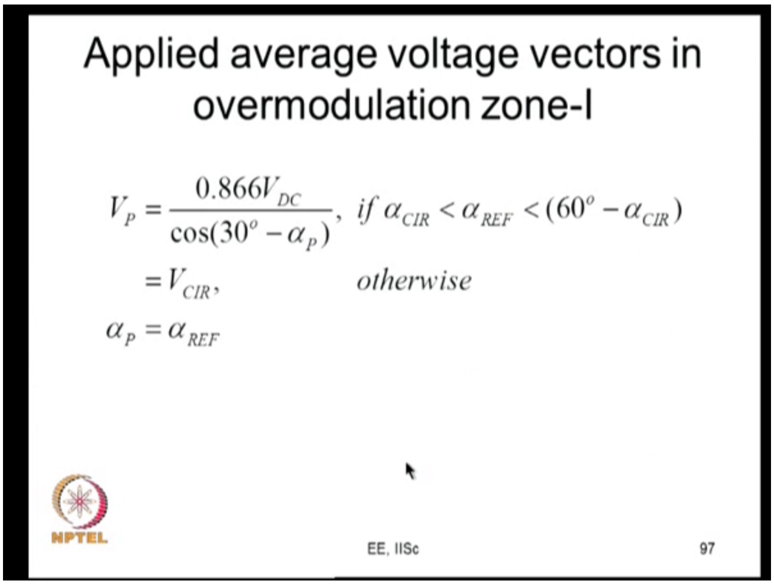

So, if you look at the voltages applied. Now this is V p and alpha p, are the magnitude and angle of the voltage vectors which are actually applied. When you are in the circular portion, when we are in hexagonal portion like here, this magnitude of the vector is given by 0.866 V DC by cos of the 30 degree minus alpha p. Your alpha p is always equal to alpha reference and this is your V p. And when you are in the circular portion of the trajectory, you are circular portion of the trajectory; your V p is equal to V circle.

So, we call this as overmodulation zone 1 in standard overmodulation algorithm.

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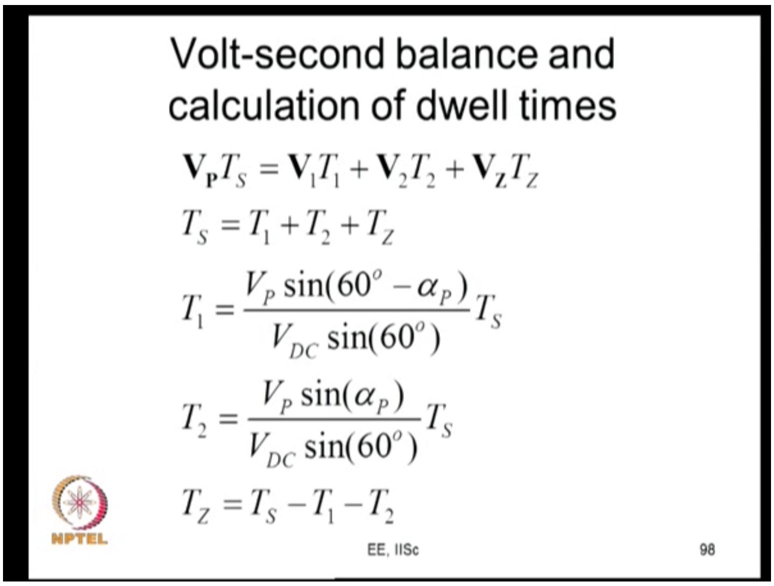

Now, you use V p and alpha p, instead of V REF and angle alpha, you use V p and try to do this volt second balance. So, we use V p and alpha p to calculate T 1, and again V p and alpha p to calculate T 2, and from there you get T z. And you could do your PWM minus space vector PWM calculations now.

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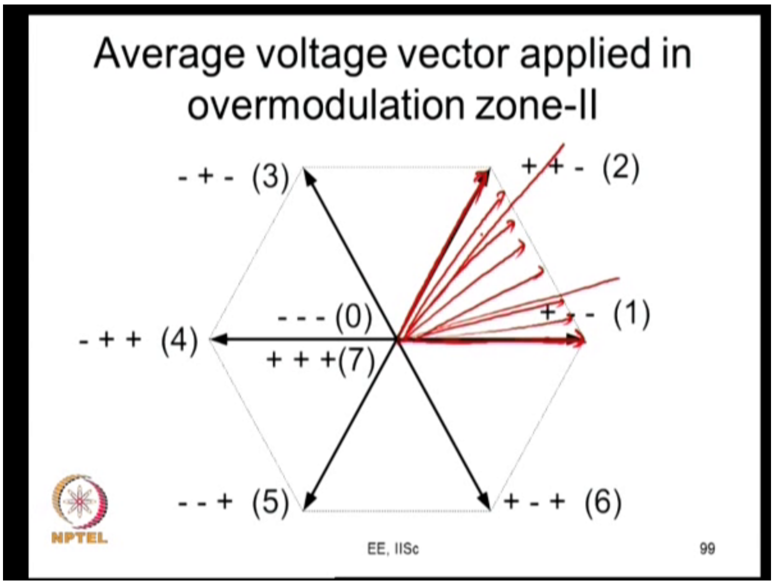

So, when you go into overmodulation in zone 2, what do you do? Is you have to make sure that all of them are like this; that is as we did as we found that was happening in sin triangle PWM, what we will do is initially for some angle. Initially for some angle, we will make sure that all the vectors are like this. That is when your references is in this angle when your references in this angle again, will make sure that all the applied voltage vectors are like this.

And in between what we will do we will make sure that the average vector go around like this; that is it will follow in entirely hexagonal trajectory the equation can be given here.

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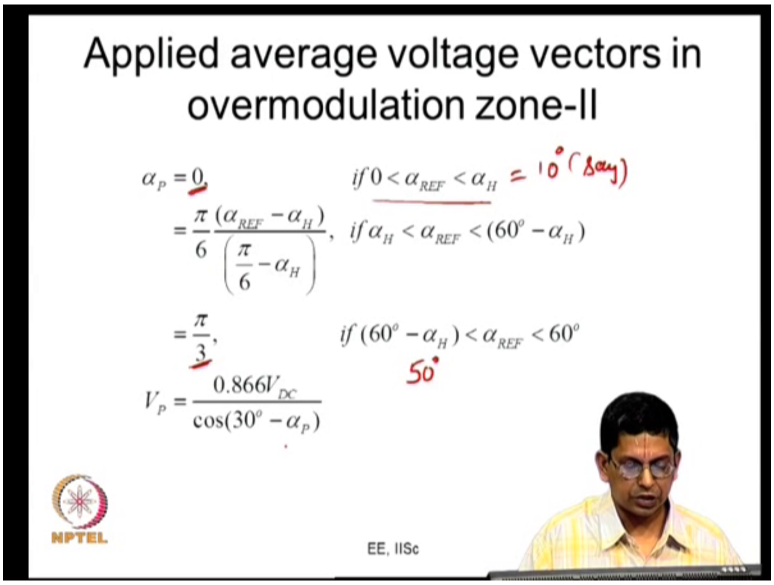

Let us say we alpha p is equal to 0, initially when your reference is between some 0 and alpha H.So, it is alpha H let us say 10 degree say. So, it is 0 and V p is 0.866 V DC by cos 30 minus alpha p if alpha p is 0 V p will also be equal to V dc. So, you are applying active vector 1. Again, the last 10 degrees from 50 to 60 degrees, you are going to apply pi by 3 and you know V p is equal to V DC your applying active vector 2. And in between your changing, the reference angle like this. So, alpha reference minus alpha H divided by pi by 6 minus alpha H.

So, if it is depending on this you know, this is what is called as standard 2 zone algorithm. This is what is most widely used in space vector base PWM methods. And it is very, very popular.

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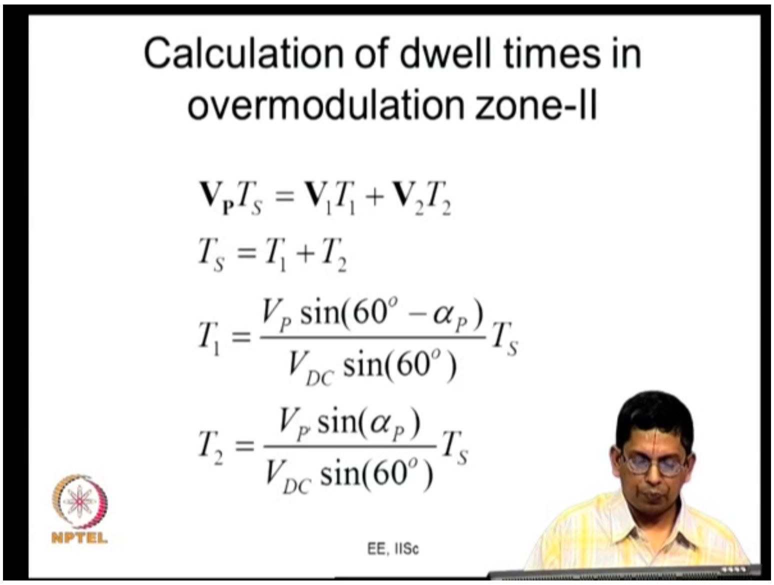

So, here once again you make use of this V p to calculate now null vector is not applied. Therefore, you are using only V 1 and V 2. And so, you are using your alpha p and V p to calculate your T 1 and T 2.

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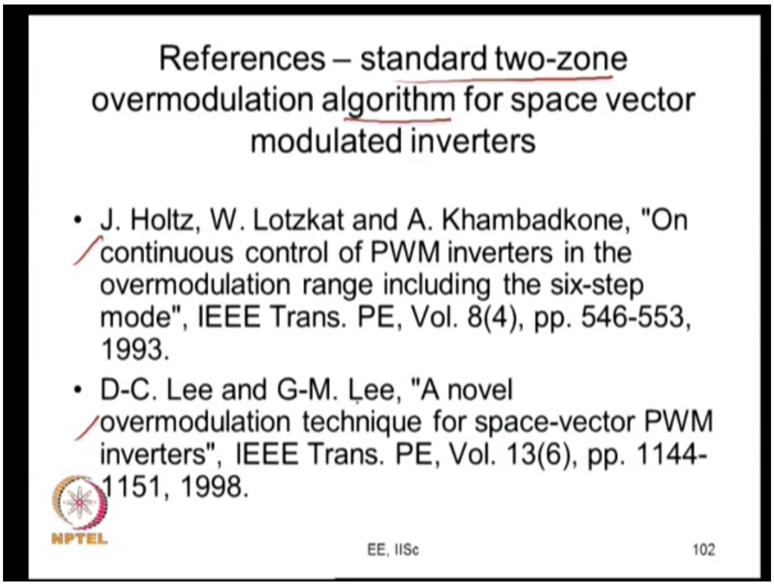

You can actually find this is standard 2 zone algorithm for space vector invertors in this, this is with this holtz latzkat and khambadkone and again, this other paper written by D-Casting; Lee and G-M. Lee.

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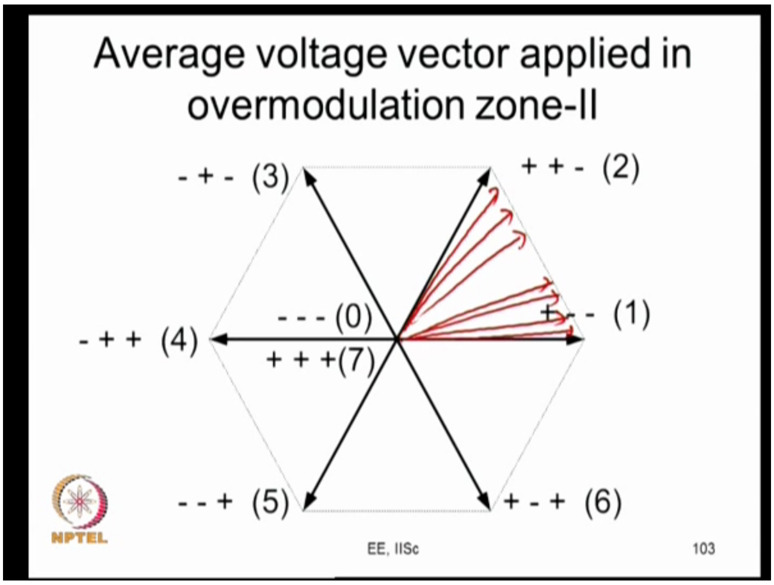

Then there are also certain other things at you can really do see, what happens is you do not have to follow the same algorithm as before. I have for example, there is another algorithm. This is K ANG into alpha REF if your alpha REF is between 0 and 30 degree.

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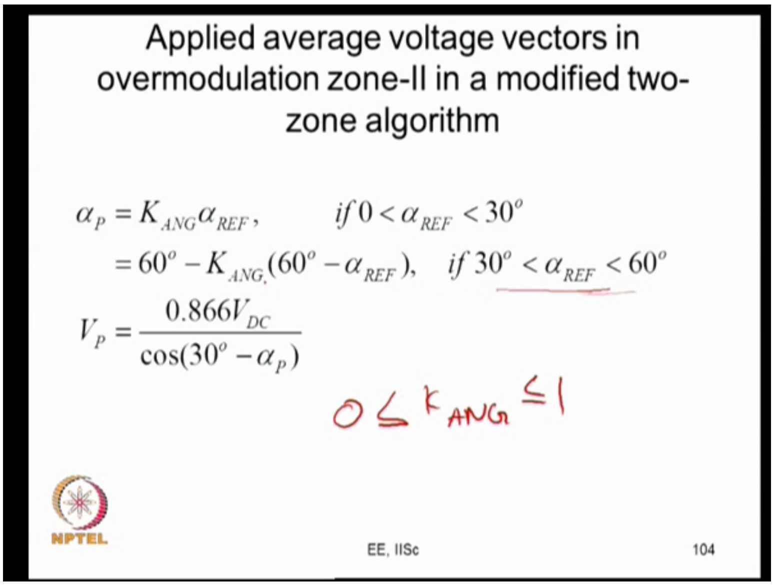

Where K ANG is a positive number 0 less than K ANG and less than 1, our less than or equal to. If I make K ANG is equal to 1, I am at overmodulation zone 1, I can change from K ANG if I reduce from 1 to 0, I will be able to increase small. Thing now let us say K ANG is a fraction. So, what happens? All the vectors in the first half get pulled closer to active vector 1. Again, all the vectors in the second half of sector one get pulled close to the active vector 2. So, I will have many of my vectors like this. The first here and again this will be more sparing here, in between it will be sparing. This is how the vector will be. And this is actually a modified 2 zone algorithm.

So, you can vary K ANG from 1, you can reduce it towards 0, to achieve 6 step mode. At 0 you will achieve 6 step mode. One advantage you will get is K ANG and the fundamental voltage vary more or less linearly in this that is one advantage here.

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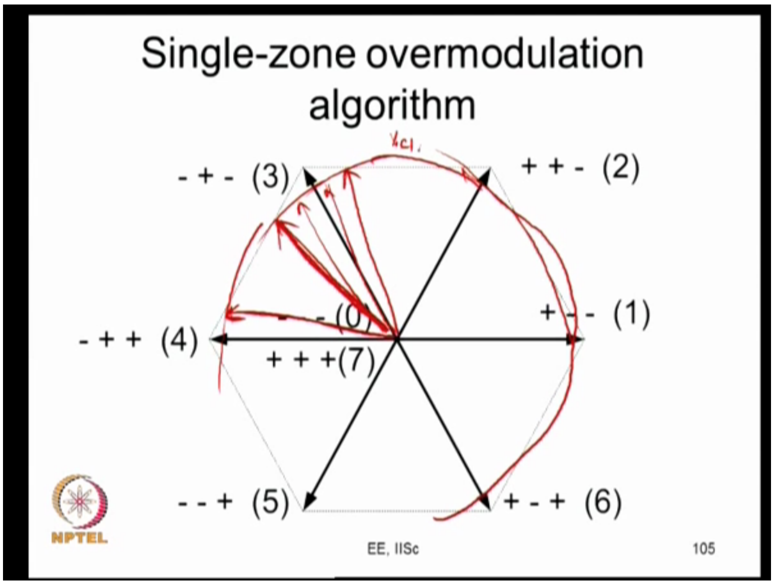

There is also what is called as single zone overmodulation algorithm, what it does is you have this circle going out, and in I am sorry for the poor circle. So, let us say it is like this. So, what you do is whenever your references here between these 2 you apply the same vector. Whenever your reference goes out of that for example, here out of the hexagon you continue to apply the same one.

So, once again it comes back you will apply this vector here. So, this is what is called as a single zone overmodulation algorithm. Here this V circle when it goes to 1, you will reach 6 step mode.

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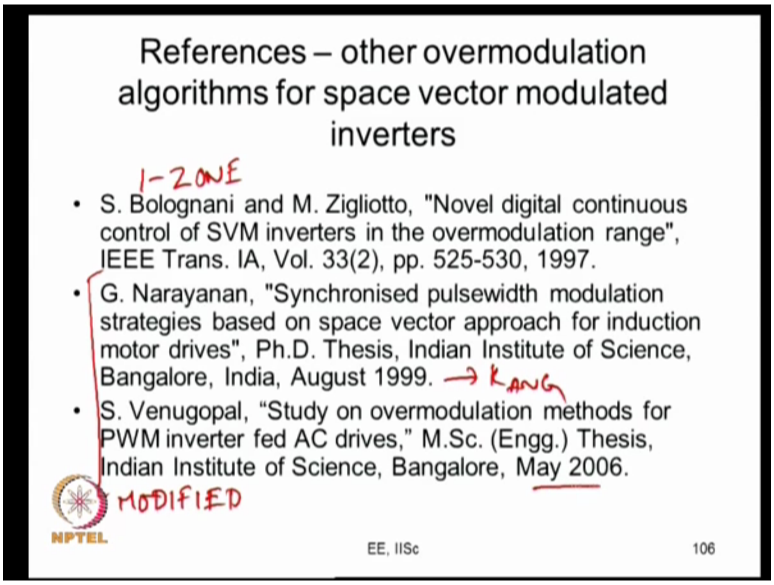

So, this single zone algorithm this is V reference for the single zone overmodulation algorithm. And these 2 are examples for modified 2 zone algorithm. So, that they are 2 different modified algorithms are discussed here. There is one kind of modification based on K ANG is discussed here. Another modification is discussed in this one.

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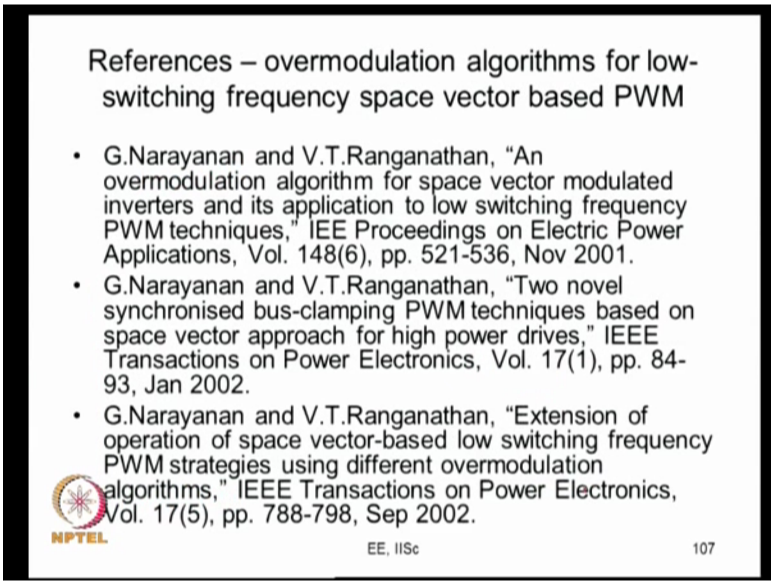

So, these are useful references for you. So, these are some more reference which deal with low switching frequency PWM. So, that is about my lecture on overmodulation methods, and I am sure the lecture I mean this reference will be useful to you. I hope the lecture was useful to you. And I look forward to continued interest for the remaining module that is on PWM of multi level inverter.

Thank you very much for you interest.