Pulsewidth Modulation for Power Electronic Converters
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Lecture – 14
Off-line optimized pulsewidth modulation

Welcome back to this lecture series on pulse width modulation for power electronic converters.

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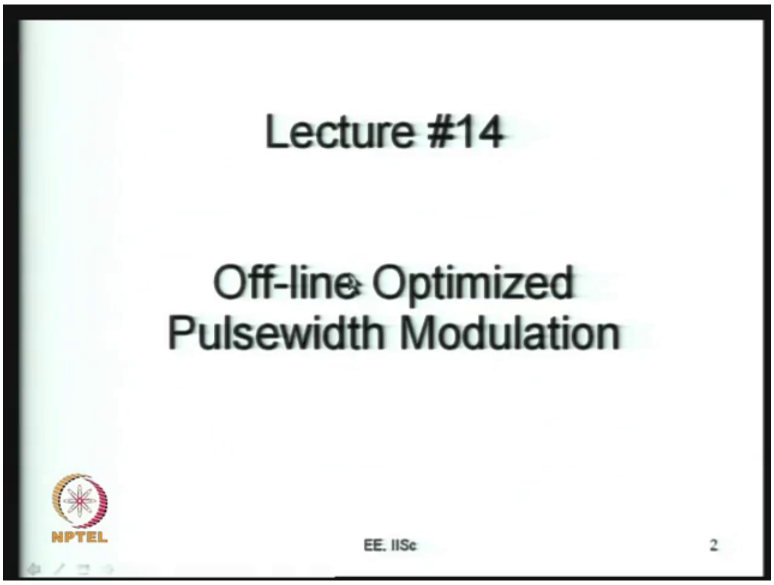

So, we have been going through, you know this is the 14th lecture; we have been going through a number of modules here. In the first module we looked at various kinds of power electronic converters, different topologies, dc dc converters and dc ac converters like two-level multilevel and all those we saw there and after that we just had an overview of just the voltage source converter.

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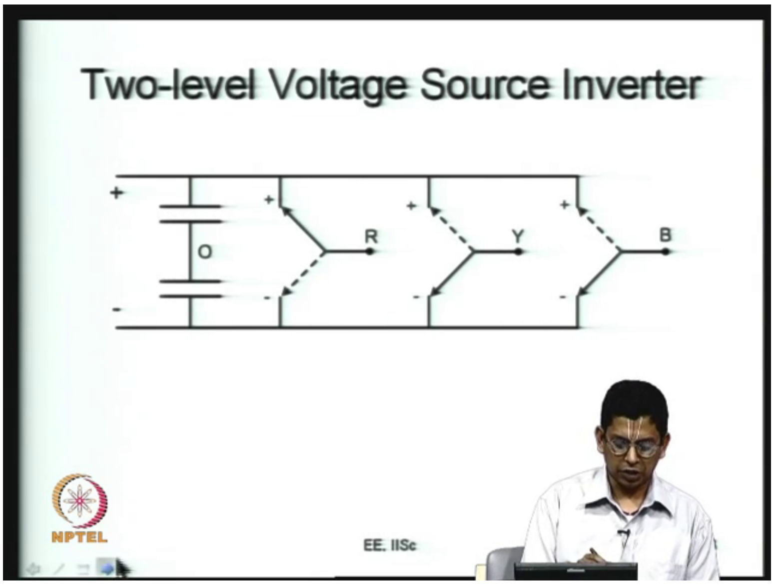

What we are looking at here as voltage source converter we just add that and after that we looked at the purpose of pulse width modulation, certain introductory ideas about pulse width modulation, why you require pulse width modulation. Basically, we want to control the fundamental voltage and you also want to control the harmonic voltages such that they are not very high and their undesirable effects are kept as well as possible.

So, we try to do that here and in this 4th module we have been looking at low switching frequency PWM methods for this now.

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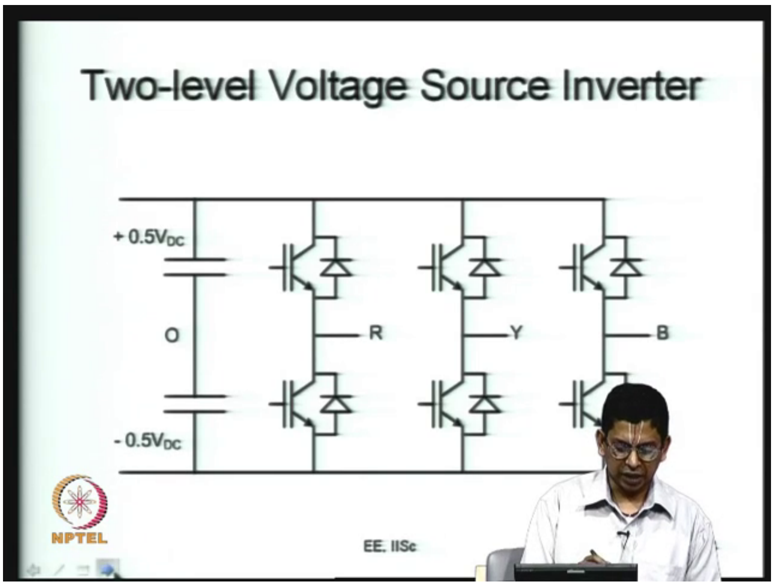

That is essentially what we have our voltage source inverter we are going to switch them and we are switching them at a frequency which is very low. So, right now we are taking only 2 switching angles per quarter cycle or the switching frequency is only about 5 times the fundamental frequency and with this we are trying to understand how the fundamental and harmonic voltages are related to the switching angles.

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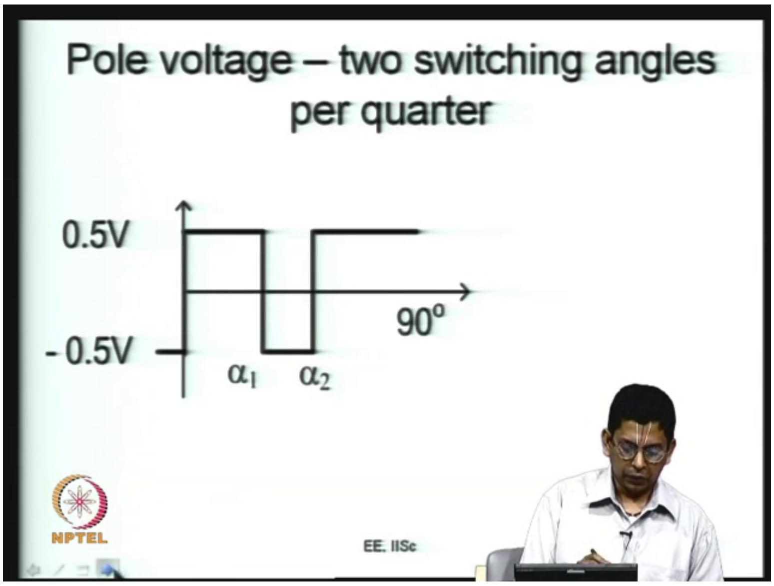

That is the whole burden of our, you know the recent past few lectures.

So, as I was mentioning we have been considering only 2 switching angles per quarter, the waveform has quarter wave and half wave symmetries. So, what it has in essence it has about 5 switching cycles within a line cycle now. So, it is switches at 5 times the fundamental frequency, as the fundamental frequency is 50 hertz this switching frequency would be 250 hertz now. So, you only have 2 angles alpha 1 and alpha 2 the other angle here being fixed at 0 that would be one other switching at 180 degrees now. With only 2 angles we keeping the problem as simple as possible we are trying we have been trying to understand how the fundamental and the harmonic voltages are related to switching angles.

So, that we can achieve the necessary fundamental voltage at the same time we can mitigate the harmonics and their ill effects.

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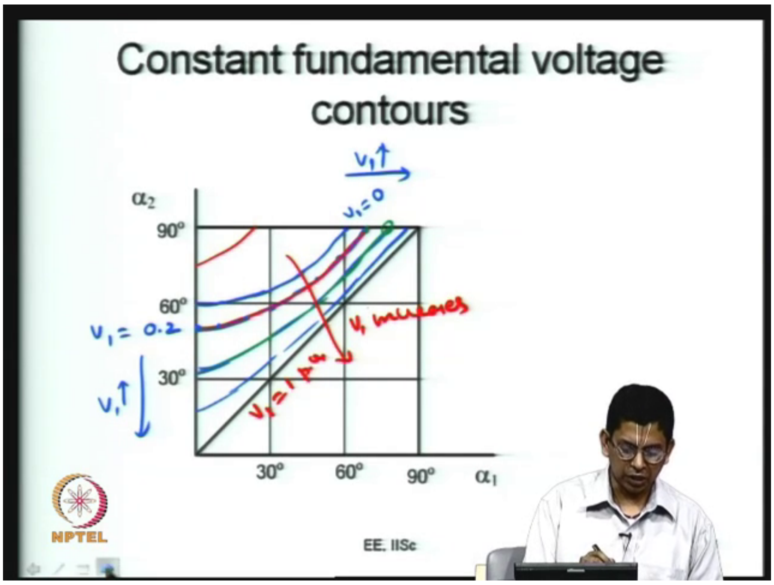

So, we were looking at how the fundamental voltage is vary, this is how the vary that is along this line on the alpha towards is alpha plane any point on this line gives you 0 fundamental voltage and any point on this line gives a 0.2 per unit fundamental voltage where one per unit stands for the fundamental voltage equal to the square wave operation there are the 6 step operation of the inverter now.

So, we have been doing all this through hand sketches we have been trying to calculate the values and sketch them by hand in the past few lectures because we want to get a good idea of what is really happening there. Now, that we have gain certain amount of insight we can start using some computer programs for plotting them.

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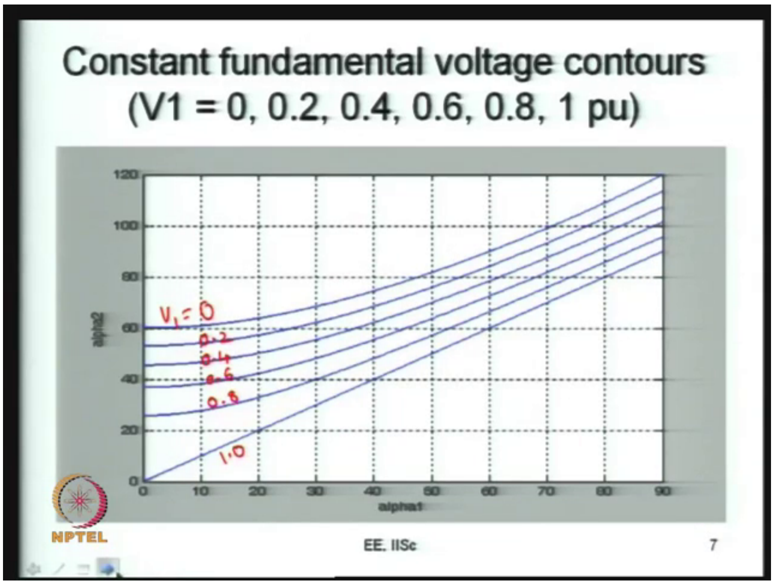

Let us say you plot this constant view on contours now. So, what I have done here is I have plotted for different values; here this is for V 1 is equal to 0.

So, this entire line is V 1 is equal to 0, you can choose any value of alpha to comma alpha 1 on that particular line, the resultant would be a PWM waveform whose fundamental component is 0 right. Then the next one that we have is 0.2 on the next line that you have corresponds to 0.4 per unit fundamental voltage, then this is 0.6 this is 0.8 and this is 1.0. So, your fundamental voltages are varying in this fashion now, if you one 0.8 it in effect it means you can choose any of these points, which point you choose that would depend on which harmonic you want to be lower or whatever you can. So, the first objective of controlling the fundamental voltage is easily attained from here. So, for V 1 is equal to 0.8 any of this on this line you can choose any point on the line, which point you can decide based on the harmonic content etcetera now.

So, which is the principle harmonic the 5th harmonic would be the principal harmonic in the third you know the 3 phase inverter, if there are any third harmonics in the pole voltages they will get subtracted vRO as some third harmonic vyo will have the same third harmonic and vRO minus vyo when you are doing you know the line to line voltage that effectively gets cancelled out. So, we do not have to worry about triple in harmonics as we saw earlier.

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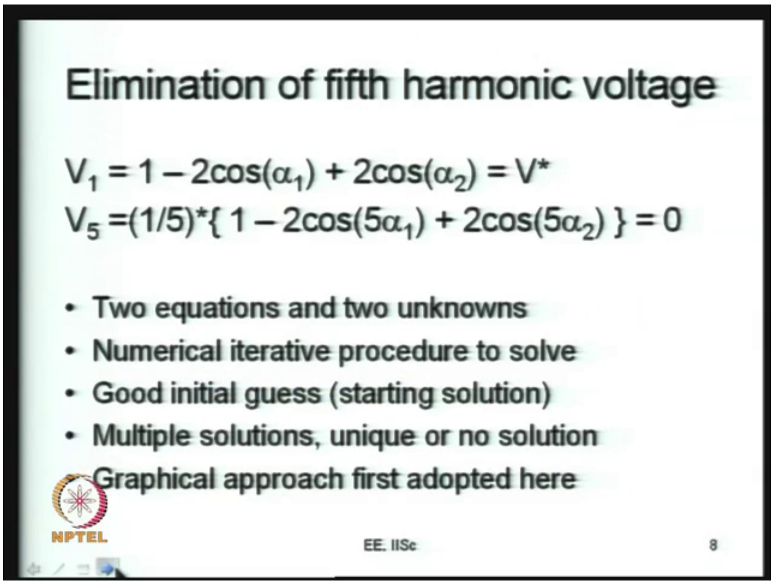

We will only to worry about the 5th harmonic now and this is the specific problem of 5th harmonic elimination which again we discussed in the last class. We want the fundamental voltage to be equal to the desired value, the alpha 1 and alpha 2 should be such that the fundamental voltage is equal to the desired value. At the same time the alpha 1 and alpha 2 have to be such that the 5th harmonic has got to be 0, this is the problem of 5th harmonic elimination. You have two equations simultaneous equations, but they are non linear transcendental equations you use a numerical iterative procedure to solve, what we are trying to do is rather than just using a procedure we are trying to understand what is happening behind the scene that is what we are trying do here.

So, we plotted all the V 5 is equal to 0 contours last 10, we tried plotting various values plugging in several numbers of alpha 1 for example, into this equation and calculating the corresponding values of alpha 2 and we found how the contours are coming up to be and now the same contours are now plotted using a computer program.

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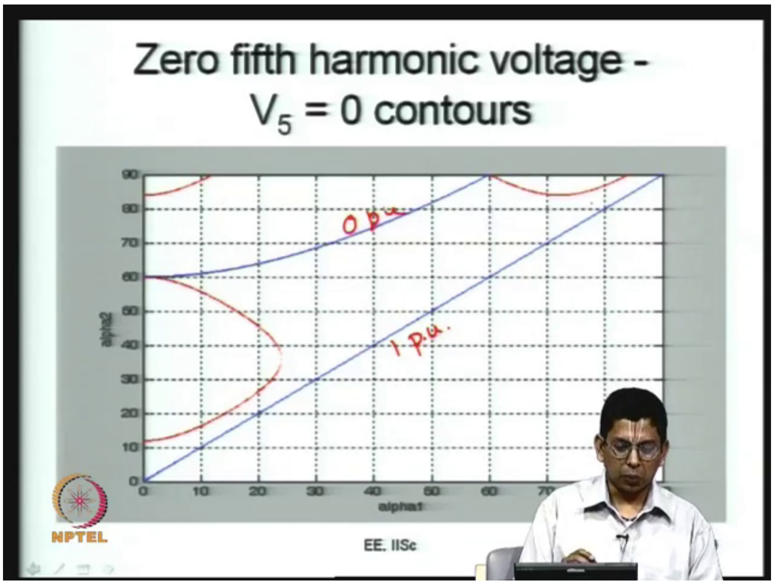

So, you know this is a V 5 equal to 0 contour, this is another contour that is along this line also you have V 5 equals 0 this contour is nothing, but the same fellow shifted up by 72 degrees shifted up by 72 degrees because 72 degrees is 360 by 5 that gives the periodicity for the you know 5th harmonic.

So, the same contour when its shifted to the right appears here it appears here and it is only a part of it, it appears here because this is our area of interest why this line marks alpha 1 is 0 we cannot have alpha 1 less than 0. So, alpha 1 is equal to 0 is one boundary and alpha 1, alpha 2 equals 90 is another boundary, again we have a constraint that alpha 2 has to be greater than alpha 1 this is alpha 2 equals alpha 1 and. So, we have to operate only in the top right angle here now and within the top right angle also you have.

This is 0 per unit fundamental voltage this is 1 per unit fundamental voltage now and on this side you are going to you will still get some waveform you may get something like point 4 point 5 per unit that you might want, but it will have a different phase as I was mentioning in a previous lecture now.

So, we are essentially going to operate not even within the top triangle we are going to operate within these 2 blue lines marked here as 0 per unit and 1 per unit now. So, these are the 5th harmonic contours that are of interest towards now. So, if you want to choose any value of fundamental voltage let us say.

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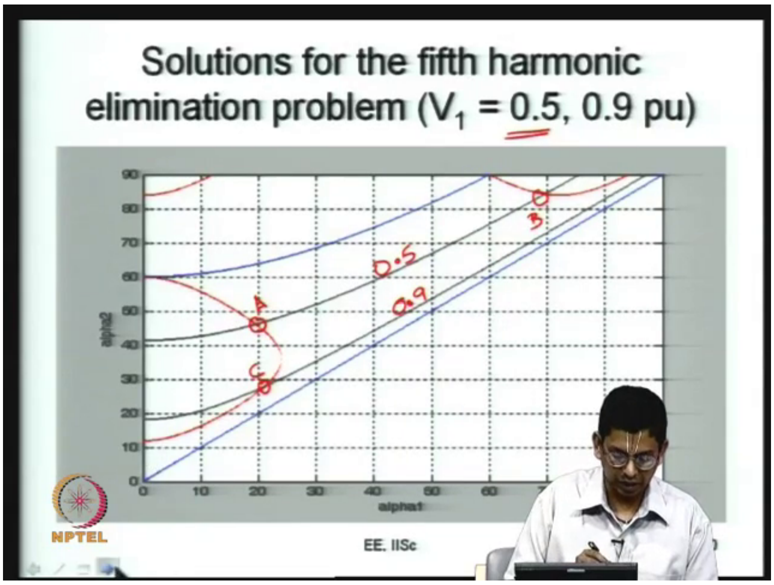

I want to choose 0.5 if I choose V 1 is equal to 0.5 and a plot 0.5, V 1 is equal to 0.5 on this I see that it intersects is 2 points these are the solutions for the 5th harmonic elimination problem.

So, along the line I can choose any point. Firstly, to achieve the necessary fundamental voltage of 50 percent that is 50 percent of the square wave right. Now, along this I have 2 different points at these 2 points I am guaranteed to have 5th harmonic to be 0, we do not know what is a 7th harmonic, we do not know what would be the 11th harmonic we would know what is about 13th harmonic, we do not know what would be the overall things now, but one thing that we can certain is let us go back to the slide if you look at the slide here. So, you see this at this point, now let me mark this point is B and let me mark this point B now, we will see a little later that A and B are equally good as far as 5th harmonic is concerned both are eliminating 5th harmonic, but you will find that b is better in terms of 7th harmonic, after 5th harmonic the most dominant harmonic is actually 7th harmonic. So, it is probably better to choose B as we will see later now.

Firstly what we have to see is sometimes your equations are possible you know it is you can get multiple solutions out of them, you may start solving a particular problem and your friend may also solve the same equation, you may come with one solution he may come with a different solution now, why is that because this equation at in certain ranges can give you multiple solutions and this is what we are trying to see now.

So, what are the range is now at 0.5 for example, it gives 2 different solutions, the 5th harmonic elimination the same 5th harmonic elimination problem if I consider a different fundamental voltage of 0.9 per unit gives only one solution. It does not intersect with the other V 5 equal to 0 contour on this side it does not intersect here it only intersects here and let me call this point as C. So, C point C is the only solution when it is 0.9 you have nothing else, whatever is the 7th harmonic whatever the 11th harmonic whatever the 13th harmonic at that point you just have to accept it. If you say that I want V 1 is equal to 0.9 per unit and V 5 should be 0 then this is the only solution for you when you are using only 2 switching angles per quarter cycle now.

So, let us see that this you know there is this so some range in which you have multiple solutions and some range you have unique solution and there is also certain range where you have no solution at all for example, you take V 1 is equal to 1 per unit and you take anything close to that something like 0.98 per unit, that will be very close to this line and that may not intersect on this red contour also, I mean it may not intersect with this also that is what we will see in the next one we will see the ranges now.

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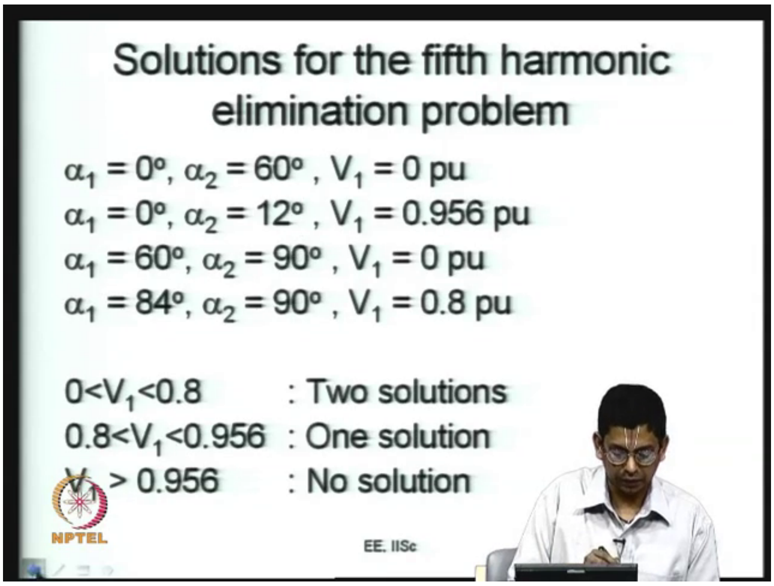

First let us say if I take alpha 1 is equal to 0 what I am getting is for V 1 is corresponding values of alpha 2, I am getting a 60 and 12 degrees that is for alpha 1 is equal to 0 this is 12 degrees this is 60 degrees and this is one of the curves now then on along this line you have alpha 2 is equal to 90 degrees. So, when I use alpha 2 is equal to 90 degrees the corresponding values of alpha 1 are 60 and 84 degrees. So, I go here.

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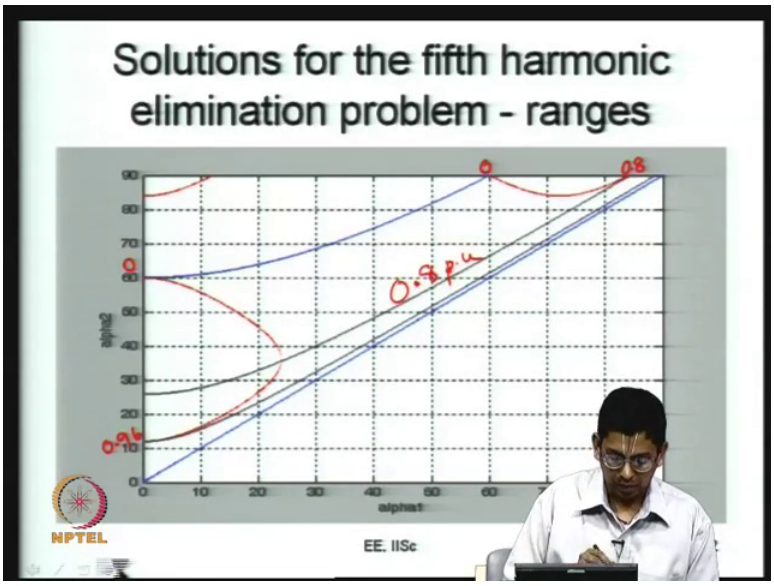

So, this is 60 degrees alpha 1 this is 84 degrees now. So, this is what we have.

So, along this curve let us see how fundamental voltage varies and along this curve how the fundamental voltage varies now. If you are starting from here the fundamental voltage is 0 as in move past in this curve you know if the fundamental voltage goes on increasing and at this point it reaches V 1 is equal to 0.8 per unit and I have plotted that 0.8 per unit line here, if you fundamental voltage increases beyond 0.8 there is not going to be any solution out of this particular curve now.

So, up to 0 to 0.8 per unit this is 0 here and this is 0.8 here, you have 1 solution as we saw before and if you are looking at this curve your this is 0 here and this is some 0.96 per unit here. So, if you are moving starting from this point we moving all the way here the fundamental voltage goes on increasing, the 5th harmonic is always 0 the fundamental goes on increasing and you reach, when you are when you are reaching when you are reaching here you get something like 0.96 per unit and beyond that 0.96 per unit there is no solution now. So, 0 to point 8 you have 2 solutions and between 0.8 and 0.96 we have one solution and beyond that you have no solutions. So, this is what we are coming up here. So, 0 to 0.8 you have 2 solutions and this 1 and this sometime no solution now.

Now, let us take the counterpart of the 7th harmonic elimination problem.

And before that let us look at these you know the 2 options how you can look at them, how do you really implement them. So, this stored waveform PWM it comes from them.

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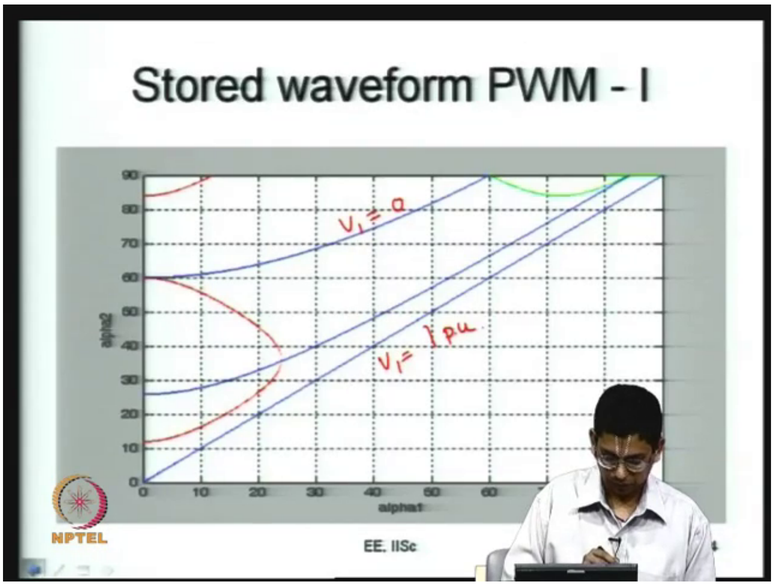

That is what you are trying to is let me just explain now. So, there are 2 solutions here, now I am focusing on one of the solutions which are marked in green here. So, what I want to do is I would start from this point and I move along this curve and I have reached alpha sorry I have reached alpha 2 is equal to 90 and that alpha 2 is equal to 90 along alpha 2 equals 90 itself I move and go and reach the end point.

So, what is that this curve along with the straight line is a locus of a point which starts from V 1 is equal to 0 sorry this is V 1 is equal to 0 and this is V 1 is equal to 1 per unit. So, this curve starts from there and goes there. So, this is we define a PWM technique, if you could recall in a previous lecture a PWM technique can be defined as any contour I mean any locus of a point which starts from one of the points on V 1 is equal to 0 contour or any V 1 is equal to V minimum contour and ends at V 1 is equal to 1 or V 1 is equal to V max, that is all that we wanted to now.

So, any line that you can draw you can just draw a straight line from here to here or you can call that a PWM technique, you can draw some wavy line from here you can call this as a PWM technique. Now, in this case we can call this as a PWM technique, this green curve can be called as a PWM technique what does it essentially say it only gives the relationship between alpha 1 at alpha 2 here and V 1 varies as we move along the curve.

So, along the locus of the point V 1 varies monotonically you start from here and you go on doing that even goes on increasing, increasing, increasing it reaches 0.8 here and from here it goes on again further increasing it goes to 1 now. So, along this locus it increases monotonically. So, if you want to implement a PWM method what you can do is you can just save this curve, what is that curve it has some alpha 1 and alpha 2 defined at every value of alpha 1 and alpha 2 on this curve there is a V 1 now.

So, let us say if you want to implement a PWM method you can save this as a look up table and hence the name stored waveform PWM, when you want V 1 is equal 0.4 then V 1 is equal to 0.4 could be some point like this, could be I am sorry V 1 is equal to 0.4 could be a point like this now. At that point you have some alpha 1 and alpha 2 what those values are you can pre compute them and you can store them in a look up table and you can output them and this is the idea of what is called as a stored waveform PWM and that is what we are trying to look at today. So, the selective harmonic elimination methods are one variety of stored waveform PWM now, you can store this green color curve in a look up table and you can output it as required now.

Alternatively what is not necessarily that this green curve you can also use this other curve.

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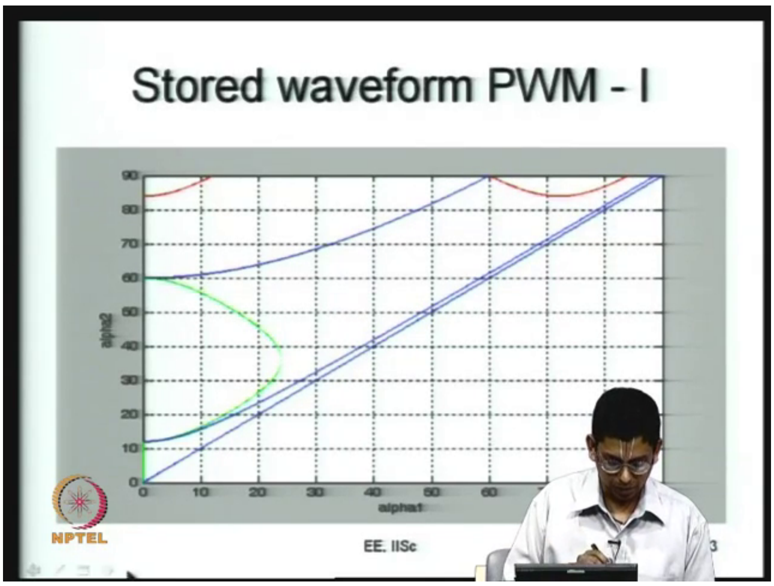

You can also use this other curve now; incidentally I have called this as PWM 1 that is PWM 2 that is we have been shifting here now. So, instead of using that curve what I am trying to do is I am using this green curve here and now this green curves if I move along this green curve it starts from 0 and the fundamental voltage goes on increasing monotonically and it finally, reaches 0.96 roughly and at beyond this point 5th harmonic elimination is not possible, but I want to still control the fundamental voltage therefore, I move along this green line to the origin now.

So, this green line is again a PWM technique and with this PWM technique the 5th harmonic is eliminated all the way from 0 fundamental unit to 0.96 per unit and the 5th harmonic is not eliminated between 0.96 and one there is certain amount of 5th harmonic is always there now. Similarly with the other curve that if you had chosen this one 5th harmonic would not be there between 0 to 0.8 and it will be there now between 0.8 and one there will be certain amount of 5th harmonic certainly there now. It is also possible for you to start with this curve and follow this curve up to some point and jump back from there to here with the same V 1 says at V 1 is equal to 5 6 or 0.7 some intermediate point you can jump over here and you can follow this curve and you can move were there now that is also possible now.

So, as I was mentioning PWM is a locus of a point on this alpha towards is alpha 1 plane and the locus starts from V 1 is equal to 0 or V 1 is equal to minimum be minimum and ends up at V 1 is equal to 1 or V 1 is equal to maximum contour. So, this is what you can do. So, this is another example of a stored PWM waveform now, these stored PWM waveforms are you know stored waveform methods are targeted at eliminating the 5th harmonic now.

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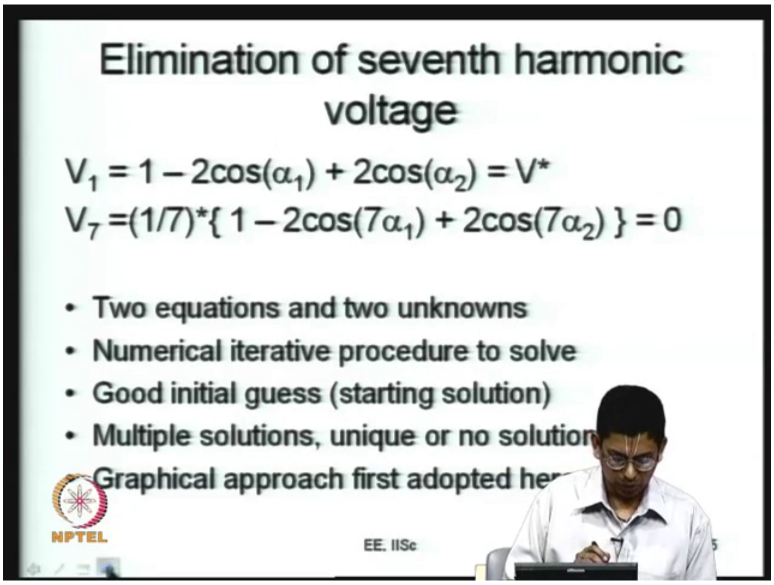

So, you can also think of the other method of eliminating 7th harmonic voltage now, it is a similar exercise, but you will see that there are differences now. So, this is V 1 you want decide V 1 to be equal to your desired V star at the same time sorry, V 7 you want it eliminated instead of V 5 mathematically it is the same procedure 2 equations 2 unknowns. So, you go about solving it iteratively you have a good starting solution you can converge faster and you go about doing that now.

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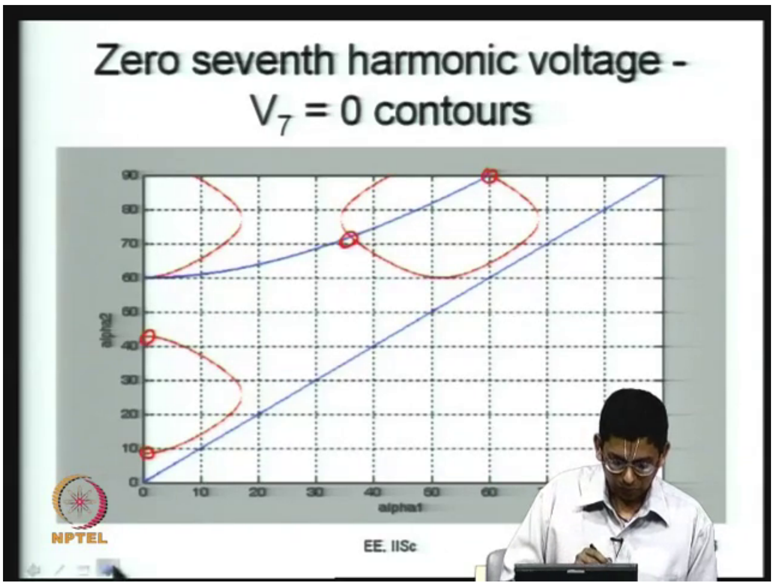

We are trying to see a graphical approach as we have been doing.

So, now, this V 7 is equal to 0 contours we plotted them again by hand in the last few classes now you can see that I have plotted them here now and many a times you know are the way I plot it would look like a semicircle and I kept on telling you it is not exactly semicircle. Now, the point we can very clearly see that point it is not exactly a semicircle now it is actually flat red the middles and it is more curved at this edges now the 4 corners that is that is what you can see and you can see that between V 5 and V 7 they are appearing more frequently because the space seeing you know the periodicity in case of V 5 equals 0 was 360 by 5 that is 72 degrees here it is 360 by 7 that is something like 51.4 degrees.

So, they are they you find closer and you find the other 2 curves also appearing prominently in the case of V 5 they appeared somewhere the corners, now the 2 curves are other 2 curves are also appearing more prominently here now. So, this is V 7 is equal to 0 contour now and any point here you will have V 7 is equal to 0, again on any point here you will have V 7 is equal to 0 and interestingly this V 7 is equal to 0 contour starts at a point here starts at a point here, at this point the fundamental voltage is not equal to 0 it again ends at a point where the fundamental voltage is not equal to one that is not surprising because when V 1 is equal to 1 its square wave operation and they 5th harmonic and 7th harmonic cannot be 0 right.

So, but it is interesting to note that there are certain V 7 equals 0 contours which do not start at V 1 is equal to 0 they start at some other point, this is something we could not see when we brought it V 5 equal to 0 contours this is one reason why one would like to plot V 1 is equal to V 5 equal to 0 some time, V 7 is equal to 0, V 11 equal to 0, V 13 equal to 0 etcetera these are exercises that will tell us you know will make us understand the relation between the switching angles and the harmonic voltage is better now you have this now.

On the other hand you have this contour now, this point here V 1 is equal to 0, at this point also V 1 is equal to 0. So, you start and if you start from this point and move along this contour here, you start from here 0 it goes on increasing it goes on increasing at some point it reaches a peak the V 1 becomes something like 0.87 or so and beyond that point it goes on reducing and at this point it becomes and on this side of the contour you still have V 7 is equal to 0 you get fundamental voltage, but this negative, what do you mean by that you will get certain fundamental voltage, but the phase will be reverse of what you will get on this side that what is called many case now.

So, if you see if you are considering V 1 is equal to 0 there are 2 points available for you here and here these 2 points eliminate 7th harmonic for you well guarantee what a V 1 you want. You take any V 1 which is small like point like 02, 2 percent or 3 percent you are going to have something very close here. So, you will have 2 different solutions possible now correct. So, which are the solution you will choose in both the cases you can get the desired fundamental voltage in both the solution you can get V 7 is equal to 0, but you might probably want to choose a solution where V 5 is also low may not be 0, but at least low. You will see that this point V 5 is 0 and anything close to this point V 5 is fairly close to 0 on the other hand if you take this point V 5 is at its maximum really and any point close to this V 5 is going to be very high we will see that little later.

So, I would say that I would probably take a point here rather than take a point here when I wanted to 7th harmonic elimination, if 5th harmonic is a you know criterion 2.

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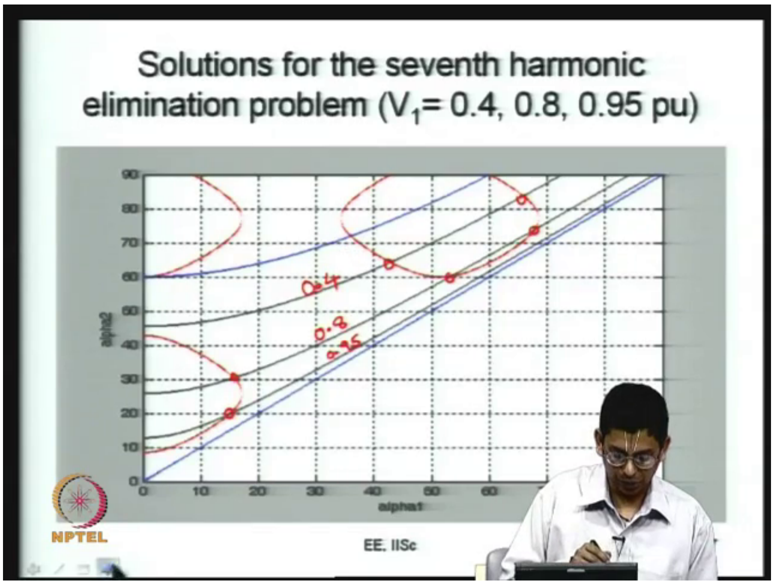

So, behind certain range now so trying to illustrate this with certain specific examples one is V 1 is equal to 0.4 excuse me, I want to take V 1 is equal to 0.4. So, V 1 is equal to 0.4 is a curve that moves like this let me write 0.4 on this. So, this is the 0.4 curve I drawn it in black.

So, it does not intersect in this side, but it intersects with this curve at these 2 points now. So, there are 2 solutions possible. So, for certain range starting from 0 to some number there are 2 solutions possible then I have been considering V 1 is equal to 0.8 and this is V 1 is equal to 0.8 I have shown plotted here. If I take V 1 is equal to 0.8 in plot that contour it intersects this curve here and it intersects this contour at 2 different points. So, there are 3 different solutions available for you 3 different solutions available for you, you have a choice to choose from great number of choices to choose from.

So, one way as I said you can probably look at what the 5th harmonic is at those points there are 3 points available x y zee and you can see at which of the points V 5 is the lowest one you can choose or you can also look at certain other criteria as I will say talk about little later you can also look at pulsating torque that is also a factor, there are other issues that you can consider and choose one of these 3 points now. Firstly, we should be aware that options are available what are the options available and then evaluate the options, for evaluating the options we should know what are the criteria that we would like to pose. So, one of them could be V 5 being 0, one of them could be the weighted THD of voltage being low other one could be the pulsating torque let us say the 6th harmonic torque being low etcetera etcetera.

So, now these 3 points are then, now let me go to another value that is 0.95 if I go to this V 1 is equal to 0.95 I have intersection only here and I this V 1 is equal to 0.95 does not intersect this contour, it does not intersect this contour at all right yeah. So, there is only one solution now. So, initially at 2 solutions and some range you have 3 solutions and in some range you are back to only one solution and finally, when you are very close to V 1 is equal to 1 there will no solution. So, 7th harmonic cannot be eliminated here.

So, let us delineate these ranges clearly. So, if you start along this curve and you move along this what are the maximum values now for V 1 is equal to 0 you have some values here alpha 1 is 60 in alpha 2 is 90 and here you have 36 and 72 degrees that is what I am written here.

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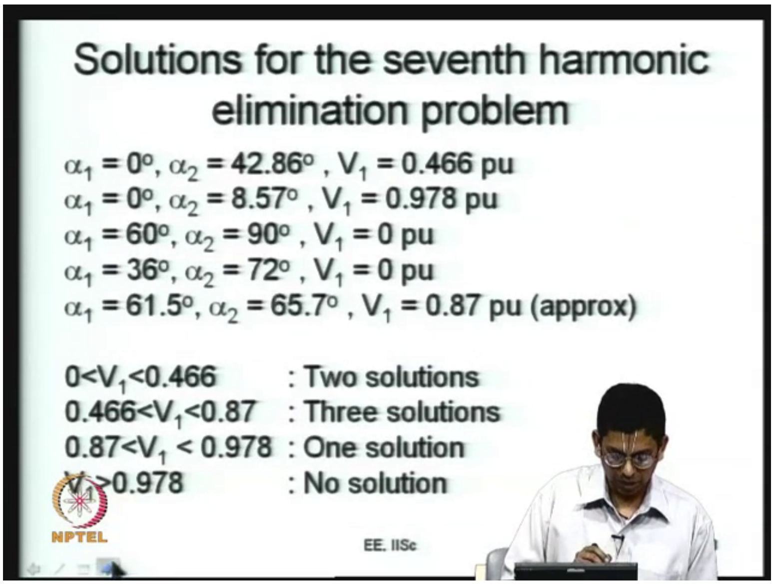

36 and 72 degrees now.

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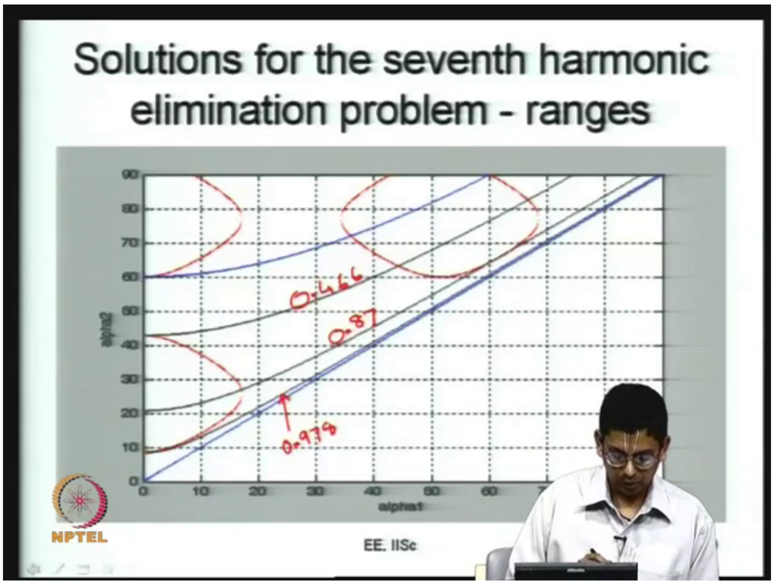

So, along this curve if you move 0 to 0.87 roughly it can give you a solution 0 to 0.87 it can give you 2 solutions, this side of the curve can give you one solution this side of the curve can give you another solution. So, this particular contour alone can give you 2 solutions in the range 0 to 0.87 and if you look at this and you look at what is the fundamental voltage at this point the fundamental voltage at that point is alpha 1 is 0 alpha 2 is 42.86 the fundamental voltage is something like 0.466.

So, up to 0 to 0.466 this fellow does not give you any solution from 0.466 all the way up to 0.978 it is 0.978 here it gives you one solution. So, this fellow gives you 2 solutions between 0 to point 0.87 and this one gives you 2 solutions one solution between 0.547 to 0.98 are so. So from between 0 to 0.46 this is 0.46. So, I am excuse me. So, this is 0.466 between 0 to 0.466 is one range, where you can get 2 solutions and then you have 0.87 this is 0.87 between 0.466 and 0.87 you get 3 solutions now and finally, you have 0.978. So, at this point it is 0.978 and this black curve, this black curves it is a little very close to V 1 is equal to 1 per unit. So, that between 0.87 and 0.978 you can get one solution and when your V 1 is beyond 0.797 8th 7th harmonic cannot be eliminated, that is what is indicated here, you have 2 solutions and you have 3 solutions and you have 1 and you can have you have no solutions no solution here right. So, let us move on.

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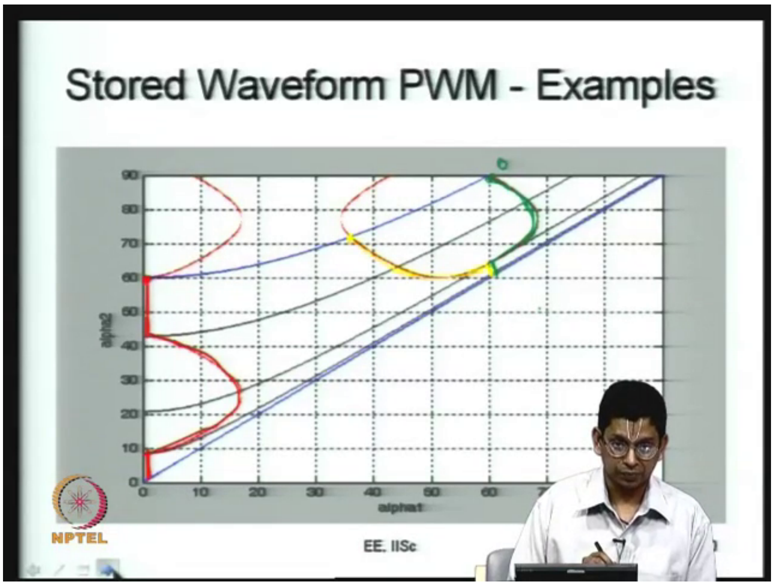

So, you can once again look at stored PWM waveform, there are several options available and I need a PWM method how do I do I have an inverter, I have a motor to run let us say using a constant voltage per hertz volts per hertz control and I need a pulse width modulation method to do that. So, one thing that I can do is let me just choose a green kind of color here, I can start from here this is V 1 is equal to 0 and I can move along this curve I can move along this curve as long as the fundamental voltage keeps on raising maybe up to some point here .

So, I would have started off with 0 and here I will have something like 0.87 per unit now up to this point this contour promises me 7th harmonic eliminated, if there will be no 7th harmonic and from here I can just move along a straight line here I am sorry I should have used a different color here just a moment yeah I am sorry about that. So, let me go back to the contour that I wanted to say. So, I start from 0, I follow this contour I follow this contour and from here I can come like this an India I can come in like this now.

So, we are able to see the green curve this is a PWM method this green curve is a PWM method I can save this as a look up table and output this, alternatively let me use another color shall I say yellow. Now, I can start from here I can go along this curve, I can go along this curve I can come back and join this V 1 is equal to 1. So, this yellow curve is another PWM technique this also guarantees me you know the necessary fundamental voltage and it guarantees me 7th harmonic would be 0 starting from 0 to something like 0.87 per unit be another it does not eliminate. So, this is another one. So, the green curve can be stored as a look up table or the yellow curve can be stored as a look up table now.

Alternatively you can also consider this method, let me use red itself here let I can start from here I can move along this curve or I can move along this what a red curve and go back here, this red is another PWM method now. So, I am giving you 3 different examples of PWM methods and these are stored waveform methods you can stored them in look up table and you can output them and you can use them now. So, they all can give you fundamental voltage ranging from 0 to 1 per unit, but you know in the case of this green and the yellow the 7th harmonic will be eliminated all the way from 0 to 0.87, but if I use the red one it is not so. It between 0 to 0.47 it is not eliminate it is eliminate only between 0.47, but up to 0.97 or so. I can also move along one of them and jump over to the other one and do this, such things are possible I mean just trying to indicate some examples for you now as to what can be done now.

So, these are stored waveform methods and you can go about doing and the green is probably the most you know preferred solution, I can easily tell you why because the range is very good it starts from 0 and goes all the way up 0.87 just like the yellow also does, but in the case of yellow curve as you can see here 5th harmonic is very high. So, the 7th harmonic may be eliminated, but the 5th harmonic is very high this could result in a very high pulsating torque as we will see a little later now just briefly look at that. So, this could be this could be very bad in terms of 5th harmonic being bad terms of the

6th harmonic pulsating torque being very high in the molten drive this could particularly bad now. So, you may not want to use it.

So, you have a options you know one you have a options you should know how to way various options and go about doing them and these are all examples of stored PWM waveforms now based on 7th harmonic elimination. So, selective harmonic elimination is one kind of.

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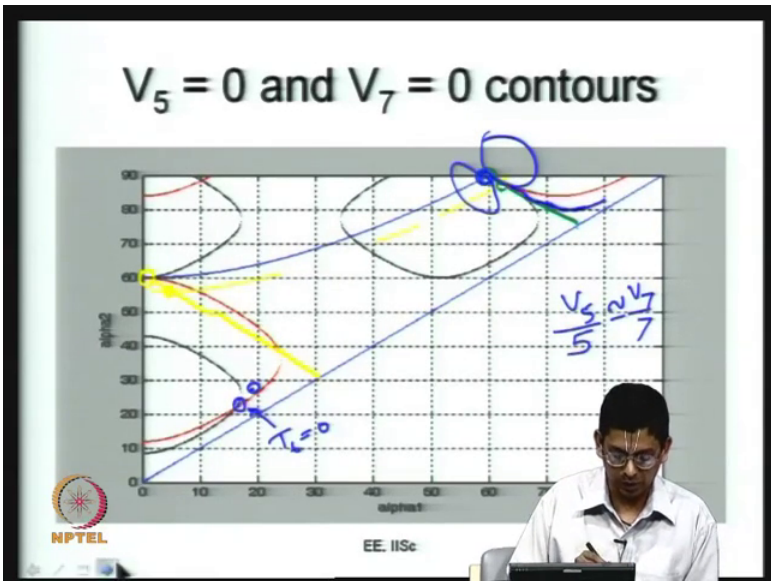

Stored waveform it is not necessarily you can also do many other kinds of waveforms you can come to you know several other PWM methods now, this V 5 equals 0 on V 7 equals 0 gives you a very good idea if you plot them they give you some kind of good idea as to how you can go about designing your PWM method.

So, now we have only 2 switching angles we want to see how best go about doing it. So, we have done this excess of plotting V 5 equal to 0 and V 7 is equal to 0 now let me start off let me use some 2 different options, one option let me call it as the green option and the other option let me call it as the yellow option what is this green option I would start from V 1 is equal to 0 right what is a PWM method it is a locus of a point which starts from this V 1 is equal to 0 contour and ends up with V 1 is equal to you know 1 let us say.

So, now I will start my green 1 low PWM technique I will start from there and the another PWM technique which I would probably say the yellow one I will I can start from here. What is the advantages of these two points at these 2 points you see that the 5th harmonic is 0 you also see that the 7th harmonic is 0, it is supposed to be it should be. So, because while this entire blue line guarantees you V 1 is equal to 0 this blue line guarantees you V 1 is equal to 0. These two are the only points on the blue line that guarantees that all the harmonics are also 0, 5 V 5, V 7, V 11, V 13 etcetera are also 0 because the waveform is a third harmonic square wave here and it is also third harmonic square wave was I told you in a previous lecture now. So, the 5th, 7th, 11th, 13th harmonics do not exist. So, not only 5th and 7th which are shown here 11th and 13th also do not exist. So, both are equally good options now.

Now, let me say I want to slightly increase that V 1 is equal to 0 is not a point at which you would operate; we are trying to understand that V 1 equals 0 mainly to understand the issues related to V 1 is equal to say 2 percent or 3 percent are small amount of voltage now. Now, let me say let me go back to this, I want to use something like V 1 is equal to like 2 percent or 3 percent now. So, if I were here what I would choose that curve can really be going somewhere like this now, this is a small voltage now I can choose some point here alternatively I can choose some point here. You see that it makes better sense to choose this point over this point let me choose the green point or the yellow point why is that so, at the green point if I choose this green point I am both V 5 and V 7 are kept reasonably low whereas, if I choose this yellow point this may also give me the same fundamental voltage I am reasonably closer to V 5 equal to 0 little farther to, but I am far away from V 7 is equal to 0.

Now, let me just finish it up this is the green yeah, now let me say I just take a straight line moving like this, I just take a straight line moving like this on the other hand with the yellow line let me just draw a line like this the green line is a PWM method and the yellow line is also PWM method as I have also mentioned before the green is good in certain respects because as the fundamental goes on increasing, as the fundamental goes on increasing you are not straying away very far from V 5 equal 0 contour or V 7 is equal to 0 contour you are not straying very far away.

So, for a up to certain substantial value of fundamental voltage this curve moves along very close to V 5 equals 0 and V 7 guarantees you low values of V 5 and V 7. So, those are the 2 principal harmonics. So, the currents are going to be dominant you know like V 5 and V 7 are more dominant or V 11 and V 13th in terms of their currents V 11 and V 13th phase higher harmonic reactances then V 5 and V 7 do.

So, if you can keep V 5 and V 7 low what is the problem? So, you can consider a method like this now again what have what you can do is you can move on here, if we consider the same yellow line what happens you are moving away an away from V 7 goes in the other direction, but your curve is moving in the other direction. So, your V 7 starts increasing very quickly though V 5 may be reasonably low, but it is increasing. So, it is going to lead to a substantial amount of V 7 and also substantial amount of 6th harmonic pulsating torque. So, that is an issue there now.

So, you can also consider certain variants. So, this is how you can look at when you draw all these curves you know what necessary and actually this point is a good point, this point is a good point because V 5 and V 7 are both equal to 0 now. So, if you can look at a trajectory which passes through that point that is also fine and this point guarantees you 0 pulsating torque because the pulsate is 6 harmonic torque is determined by the 5th harmonic voltage and the 7th harmonic voltage. If they are both equal to 0 6th harmonic torque should be 0 it is actually a good point to operate in. So, you can look for any curve that goes through that goes close to this and things like this now.

So, several possible contours you can draw infinite number of contours you can start form any point on V 1 is equal to 0 and you can choose any point on V 1 is equal to 1 and from that point to this point you there are several contours again infinite number of contours. It basically tells you that the infinite number of PWM techniques are possible, but not all PWM techniques are equally good right, how do you choose those good techniques now? So, not only a control of fundamental voltage in terms of harmonics also that is be the burden of over thing now. So, if you look at V 5 and V 7 just for example, only 2 of them it makes it crystal clear that these are the only 2 points which are worth operating at when you are looking at V 1 is equal to 0, when you are looking at V 1 is equal to some small number again you need to be close to one of these 2 points and it is better that you are close to this point rather than close to here because if you are close to here both your V 5 and V 7 are guaranteed to be low, on the other hand if you are here your V 7 could be much higher this is now.

So, it gives you an idea for to know on this know you can also plot V 11 and V 13th and you can see you can get a better picture of what exactly happens now, you generally see that in your here at low modulation indices when you are operating somewhere here it is very good it is something very good now. So, let me just plot V 11, V 13th and such kind of curves now if I really plot them you know how we they would look most of the curves will actually go like this now those are loops I have indicated, this is like V 11 is equal to 0 V 13th is equal to 0 and go on and all the curves will move tangential at this particular point now. So, at that point all the harmonics are 0 and you can see that if you are locus the PWM the locus that 10 or the line that indicates the PWM technique itself moves tangentially to all the vn equal to 0 contours.

So, along the line the harmonic is not increasing very highly. So, that is one of the reasons. So, for at low modulation indices almost all the harmonics are very very close to 0 here now, as you will see in what is called as the minimization of weighted THD you would get many points normally close to this now. That is if you are operating here your overall THD V 5 is guaranteed to be low, V 7 is guaranteed to be low, V 11 is guaranteed to be low, V 13th is guaranteed to be low and overall the weighted THD is guaranteed to be low here at low modulation indices that is not the same when it comes to high modulation indices.

Now, let me say if I take this point here obviously, square wave. So, 5th cannot be 0 7th harmonic cannot be 0 and similarly come close to higher modulations this is may not be the case now, on the other hand if you consider anything here you consider this band here you consider any point here you are assured of V 5 as well as V 7 being reasonably low and these are high modulation indices now. If you plot V 11 equals 0 V 13th etcetera equal to 0 also you will see that in this area you will see many of the vn equal 0 contours passing here now.

So, this essentially tells you that at high modulation indices if you operate closer to this origin you operate closer to this origin in this region you are guaranteed to get better results many of the harmonics could be lower. At lower modulation indices it is better that you operate closer to this particular point at higher modulation indices you operate in this range now. So, if I may have to give you something indicatively at lower modulation indices if I take this angle what is that this is 60 this is 90, both my alpha 1 and alpha 2 are within the range 60 to 90 degree. If I choose my alpha 1 and alpha 2 be within the range 60 to 90 the lower order harmonics are likely to be much better at low modulation indices I mean and similarly if I am talking high modulation indices it is better that operate somewhere in this range, it is better that I operate somewhere within this range that is 0 to 30 degrees, I have to make sure that both the switching angles are probably within 0 to 30 degrees and closer to them now that is how you will get now right.

So, this is basically to give you on this I would certainly encourage you to plot V 11 equal 0 and V 13th equal to 0 contours etcetera you can certainly make use of you know way we were looking at V 5 equal to 0 V 7 equals 0 it is also possible to plot for you roughly where it comes and you can also use a computer program to plot it precisely. So, you will see what happens in how exactly it is going to come through and you see this where should now.

So, there are many many PWM methods and the you know and it is possible to when some of them will be better than the other and we are trying to get some idea as to how one could design better PWM methods now.

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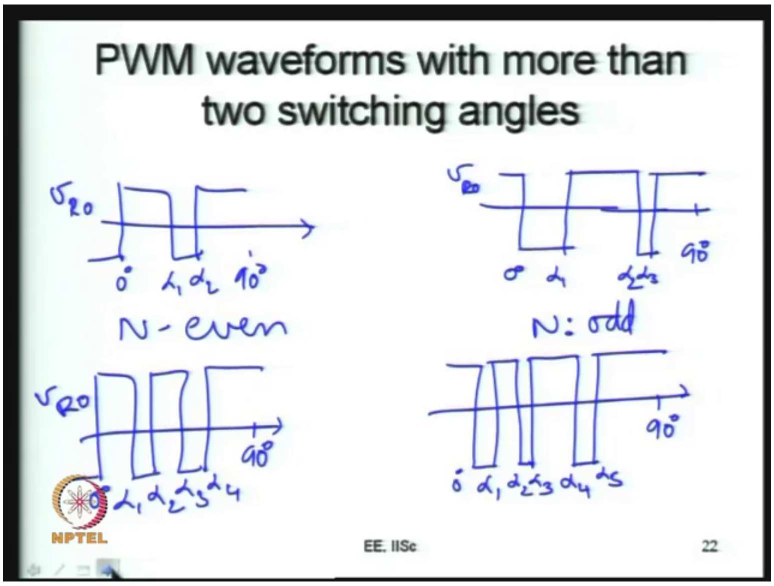

So, if you are looking at this is only up to 2 switching angles now you want to go more than 2 switching angles because this 2 switching angle you must realize that we took it up only as a means to improve or understanding. We just wanted to understand the relationship between the fundamental voltage and the harmonic voltages on one hand with the switching angles on the other hand. So, we kept the problem simple by only 2 switching angles now.

So, what is this 2 switching angle stuff we have been considering a pole voltage which is like this, we have been considering pole voltage vRO is like this now this is 0 degree this is alpha 1 this is alpha 2 this is 90 degree, this is what we have been considering. Now, if you want to consider 3 switching angles here vRO is switching from 0 at 0 it is switching from negative to positive it is common to consider the switching the other way at 0 degree vRO would normally switch in the other direction and this could be your alpha 1 this could be your alpha 2 this is 90 degree. Alpha 1, alpha 2 I am sorry alpha 1 it goes back alpha 2 comes and then alpha 3, 90 degree its normal to use it the other way that is at the 0 crossing your vRO will be switching from positive to negative now. So, this is for 3 switching angle problem now.

So, you have alpha 1 alpha 2 alpha 3, V 1 is related to alpha 1, alpha 2, alpha 3 vn is related to alpha 1, alpha 2, alpha 3 you can do all that you want to do the harmonic elimination. So, 5th harmonic and 7th harmonic 2 harmonics can be eliminated with controlling fundamental voltage now. So, with 3 switching angles 2 harmonics can be eliminated this is the nature of waveform will use now.

Now, let us say you want to use 4 switching angles. So, what you can probably do is you go like this. So, this is 4 switching angles per quarter alpha 1, alpha 2, alpha 3, alpha 4 and this is 0 degree. So, generally for e 1 value for where n is the number of switchings per quarter and it is even value you choose this kind of a PWM waveform where vRO switches from negative to positive and in general for the other side you will switch it the other way alpha 1, alpha 2, alpha 3, 0 alpha 1, alpha 2, alpha 3, alpha 4, alpha 5, 90 degrees.

So, for N is odd you are using this kind of waveforms and you can use for any value of N now. So, these are more and more switching angles now the exercises that we did for N is equal to the for 2 we can do similar exercises for n is equal to 3. We can plot here we could plot on for n is equal to 2 we could just plot it on a single plane here it has to be plot in a 3 dimensional space, but still you can use your computer programs to plot those and get an idea of how V 5 equals 0 and V 7 equals 0 contours are here. How they would be you know instead of being a curve in this case sorry instead of being just a curve here it would become a surface here, it would become a surface in the 3 dimensional space here and for all these you can just formulate the equations and you can go about solving them.

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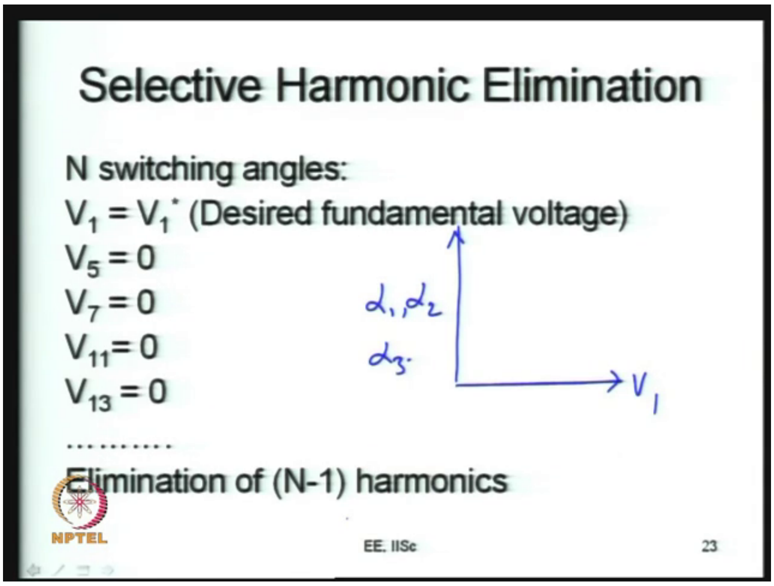

If you look at the selective harmonic elimination and you look at n switching angles. So, you can have N number of equations. So, V 1 is equal to V 1 star is they desired fundamental voltage this is one of your equation then you can go about eliminating N minus 1 harmonics capital N minus 1 harmonics where n is the number of switching angles per quarter you can eliminate 7th, 5th harmonic 7th, 11th 13thth and up to n minus one harmonics we can go about eliminating. You can solve all these equations it is capital N number of simultaneous equations these are all transcendental equations and you can solve them and you can come up with solutions now, again you may come up with different solutions.

So, sometimes it may give you same set of equations you may come up with one solution your friend may come up with another solution because you know one reason could be that your starting solution and in his starting solutions very different. So, depending on numerical procedure and the starting solution that you take you would converge on to one or the other kind of solutions here now. So, we are now better we know that multiple solutions are possible and all such awareness that we suddenly have and with an idea of all this V 5 equals 0 V 7 equals 0 where are the harmonics being 0 it is also possible for us to such as good values of starting solutions now ok.

So, many a times if you want to eliminate all the harmonics you can also start, let us say V 1 is equal to point 5 per unit is what you want to start you want to do. So, and all some N minus 1 harmonics have to be 0 you can also start at a point where the waveform is effectively a third harmonic square wave or a 9th harmonic square wave or so on. In that case all the harmonics are anyway guaranteed to be 0 and the fundamental voltage is 0.

So, once you know the solution for that you can calculate that is V 1 star is equal to 0 the solution is very obvious and then you can calculate for V 1 star is equal to some small value 0.01, 0.02 and you can go about calculating. So, this can give you the solutions for various values of 1 one also. So, typically in the books you will find solutions for against V 1. Now, let me just write it down here now what you will find is against V 1 different values of alpha will be plotted here alpha 1, alpha 2, alpha 3 etcetera would be plotted against this now. I am not doing this here you can certainly go about and doing this as an exercise and it is available in several other references which I am going to mention now there all right ok.

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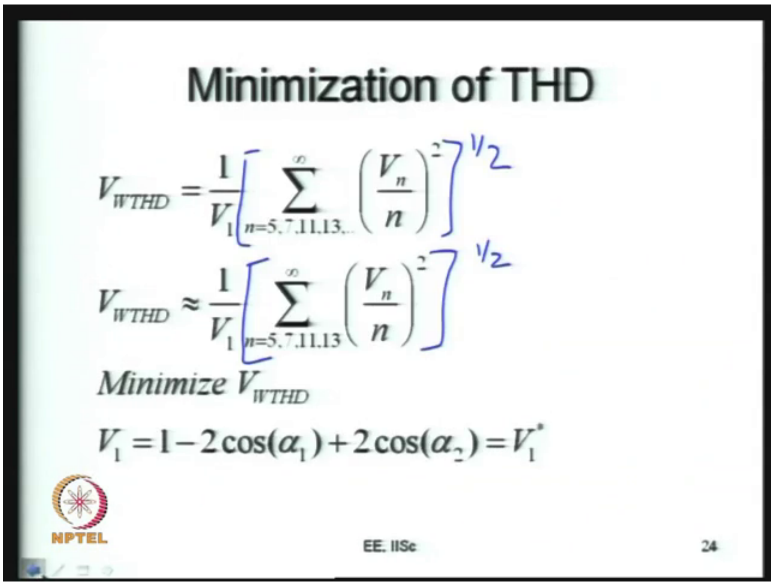

So, now if you move to the next point now, this is about selective harmonic elimination that is not the only stored waveform quality what you can do is you can go about minimizing THD you can go about minimizing the THD. The THD is the line current the

THD in the line current is equal to the weighted THD w stands for weighted, weighted total harmonic distortion in the voltage waveform. Now, if you see that there is a factor V n, what is this V n? V n is the nth harmonic voltage the nth harmonic voltage sees a harmonic reactance which is n times that seen by the fundamental voltage. So, you have V n by n factor here and that is whole square. So, this gives you basically that the I have missed out a square root on this I am sorry. So, what do you normally have is you would have a square root on this you would have a.

So, this V n by n, V n by n is indicative of the nth harmonic current and the sigma V n by n the whole squared is indicative of sigma I n squared is the measure of sigma I n squared that is all the harmonic comes added together the total ripple correct. So, that is normalized with respect to the fundamental voltage now, this is called the weighted THD of the voltage waveform which is equivalent to the current THD. If you multiply the weighted THD by a factor which is roughly equal to the no load impedance divided by the block total impedance or the machine you will get your current THD roughly.

So, now theoretically it contains all the values of n, but you will see that higher values of n know they you know the V n itself will be low and V n by n will be very low. So, they can be ignored. So, I have just shown like V 5, 7 11, 13th you can probably stop here I mean you can consider more values I am just trying to tell you that n can be truncated at some point in approximately.

Now, you choose your alpha 1 and alpha 2 such that they guarantee going to the same switching angles the alpha 1 and alpha 2 they guarantee the required fundamental voltage at the same time they minimize this weighted THD. That is you look at the entire possible solution of entire set of all values of alpha 1 and alpha 2 which will give you the required V 1 star and you choose that particular value which gives you minimum amount of weighted THD that is what is called as offline optimal PWM for optimizing minimizing things.

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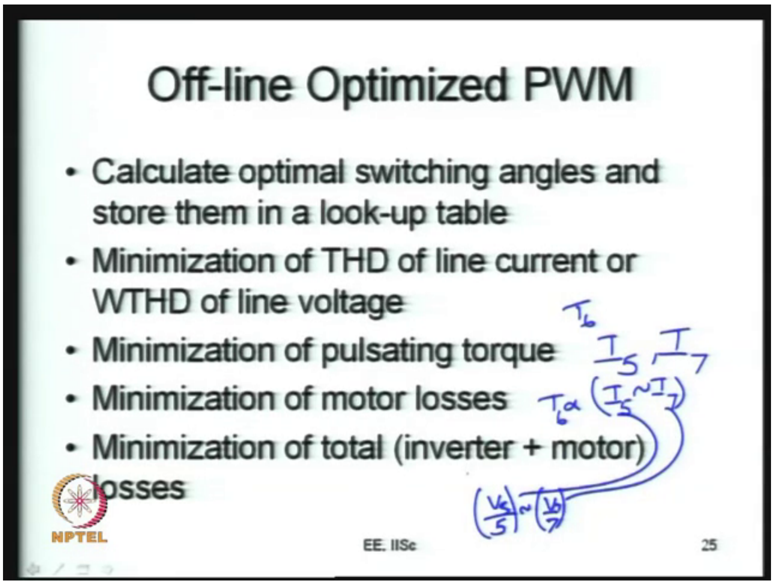

So, you can do an offline optimization you can calculate the optimal switching angles.

So, for V 1 is equal to 0.1 per unit what is my alpha 1 optimal an alpha 2 optimal V 1 is equal to 0.2 per unit what should be my alpha 1 1 and alpha 2 optimal and you can store all of them in a look up table. So, this is again a stored waveform PWM method. So, this waveforms will give you not just eliminating 5th harmonic and 7th harmonic they will not be eliminate, but they will try to minimize the weighted THD. 5th harmonic may not be 07th may not be 0, but the overall weighted THD of the voltage waveform or the current THD or the THD of the current waveform will be very low. So, this is what is an offline optimal PWM method now.

So, minimization of THD of line current or weighted THD of line voltage is what is done here, alternatively you can also try in minimize pulsating torque, how do you do by minimizing pulsating torque you will have to understand what causes pulsating torque, what causes pulsating torque? Had the motor been operating with sinusoidal voltages there is going to be no pulsating torque at all its going to be steady torque only because the motor is operating with non sinusoidal voltages you are getting pulsating torque what are the effects of a non sinusoidal voltage the flux is non sinusoidal and the currents are also non sinusoidal.

So, if you consider the flux you have a sinusoidal component you also have a non sinusoidal components again similarly consider the currents the motor currents they also have fundamental and non sinusoidal. The fundamental flux on the fundamental current interact to produce the steady torque whereas, the fundamental flux and the ripple current, harmonic current produce the pulsating torque the same way the fundamental current and the harmonic fluxes interact to produce the pulsating torque. Also we you know harmonic fluxes and the harmonic currents can interact, but they are negligible because harmonic fluxes will be negligible and harmonic currents will be negligible and their product would be much more you know negligible you do not have to worry about.

So, what causes pulsating torque is one is the fundamental flux interacting with harmonic current and the other one is the fundamental current interacting with harmonic flux and analysis can show you that the fundamental flux interacting with harmonic currents is what is really higher. So, it is really cause of harmonic current now. So, now, let me say I have these harmonic currents 1 is I 5 5th harmonic current what does this 5th harmonic current do this 5th harmonic current would interact with the fundamental flux and the relative speeds would be 6 times the fundamental frequency and this will end up producing a 6th harmonic pulsating torque.

The same way the 7th harmonic current will also do the same job the 7th harmonic current and the fundamental flux both revolve in the same direction they have a relative speed of 6 times the fundamental frequency. So, this I 7 fellows also interacts the fundamental flux and gives you a produce a 6th harmonic torque. So, both I 5 and I 7 are responsible for 6th harmonic torque. So, if you want T 6 to be 0, ideally what you should do is make sure that I 5 and I 7 are 0 you want to make I 5 and I 7 0 what you should do is V 5 and V 7 both should be 0, but it may not be possible particularly if you are considering only 2 switching angles it is not possible.

So, if you analyze the problem clearly you would see that T 6 depends on the difference between I 5 and I 7 it actually depends on the difference between I 5 and I 7. So, if you can make sure the difference between I 5 and I 7 is very low, you can make sure that the difference between I 5 and I 7 is very low then you can eliminate 6th harmonic pulsation now. So, let me just change this further now. So, what is I 5? I 5 is basically V 5 upon 5 and V v 7 is basically V 7 upon 7.

So, if you if your 5th harmonic and 7th harmonic are such that V 5 by 5 and V 7 by 7 are close to one another then the 6th harmonic pulsating torque is reduced I am trying to simplify the arguments and giving a very simple picture now. So, with 2 switching angles itself it is possible for you to make sure that the 5th harmonic and the 7th harmonic are both close to 0, you know then you can get this kind of a waveform that you here now let us go back to the V 5 equal to 0 and V 7 equals 0 contour and there we will see this point now.

So, here I want to point out to you that say let us say this point excuse me. So, if you say this point as I pointed out to you T 6 is equal to 0 there T 6 is equal to 0 at that point, why is T 6 is equal to 0 because both V 5 and V 7 are equal to 0 and therefore, I 5 and I 7 are equal to 0 and therefore, 6th harmonic torque is 0. Now let us say you consider a point something close to that you consider a point something close to this point V 5 is not 0 and V 7 is also not 0, but it is quite possible that the V 5 and V 7 amplitudes you have to search around that point you have to you it is possible for it to find a point where V 5 and V 7 are such that V 5 by 5 is equal to V 7 by 7 and also V 5 and V 7 are the same phase if you kind of come up with such kind of a point then you can say that the 6th harmonic torque gets eliminated there also.

Similarly, this point you have a 6th harmonic torque is 0, why because V 5 and V 7 are both equal to 0 and somewhere on this line you may come somewhere you know you will get a set of points here along these points that you indicating the V 5 and V 7 are such that V 5 by 5 and V 7 by 7 are roughly equal V 5 by 5 is roughly equal to V 7 by 7 you can get a set of points now this is what would be 6th harmonic torque being 0 now.

So, you can look at selective elimination of harmonic torque and you can calculate the switching angles and you can save them as a look up table that is also stored we found PWM method. instead of considering particular pulsating torque I am sorry instead of considering 6th harmonic torque you can also consider the sum of all the torques, 6th 12th everything you can consider the rms torque or the peak torque and you can try to minimize you come up with switching angles alpha 1 optimal, alpha 2 optimal, alpha 3 optimal etcetera that would minimize your pulsating torque the peak value of the pulsating torque or the rms value of pulsating torque whatever it could be are specifically 6th harmonic torque or 12th harmonic torque. That also can be called as an optimized PWM offline optimist your calculating all these offline when you are storing them as a look up table and using a during an implementation now.

And you can also attempt to minimize the motor losses, these harmonics are causing certain amount of motor losses increase copper losses and there is also increased core losses you can if you understand the relationship between the switching angles and the motor losses if we can express this mathematically then it is possible for you to come up with alpha 1, alpha 2 optimal values which will give you apart from the necessary V 1 which can also minimize the motor losses now.

You should know how to express motor losses in terms of switching angles you can also look at the total losses which is the inverter plus motor losses now. So, if you look at the inverter plus motor losses you should once again be able to express the total loss as a function of the switching angles then you can minimize you can treat this as an optimization problem and minimize and you can calculate your alpha 1 optimal, alpha 2 optimal, alpha 3 optimal at every possible values of V 1 like 1 percent, 2 percent, 3 percent, 4 percent save it as a look up table and use it during the waveform now.

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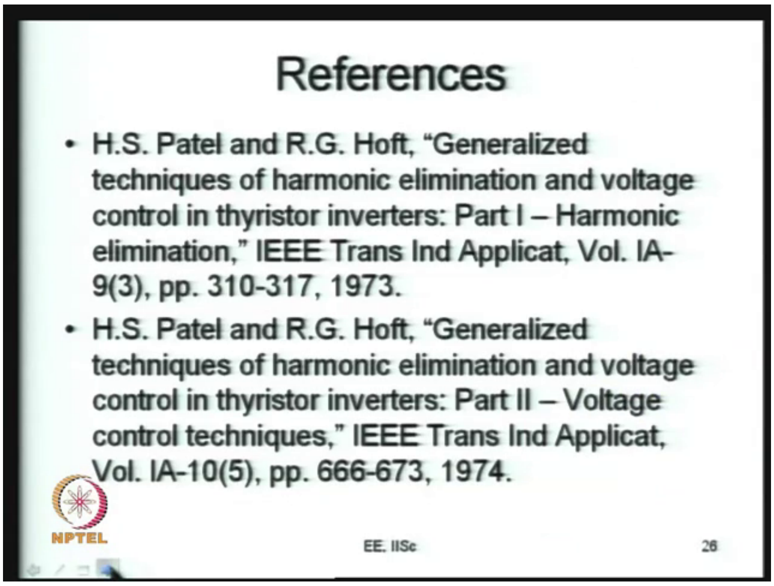

So, that is what we have about offline optimal PWM, here I am going to suggest some good papers which has seminal work and there are also other papers in this area, but I am just going to suggest a few of them for you to go and read and so that you get a better understanding of this. So, these are some of the earliest papers on harmonic elimination method now there is part 1 and part 2 which particularly dealt with harmonic elimination and voltage control methods now these are published in the years 1973 1974 by Patel and Hoft.

So, these are among the oldest there are still older paper here in 1964 etcetera, but I am just giving you this paper this is one of the references now.

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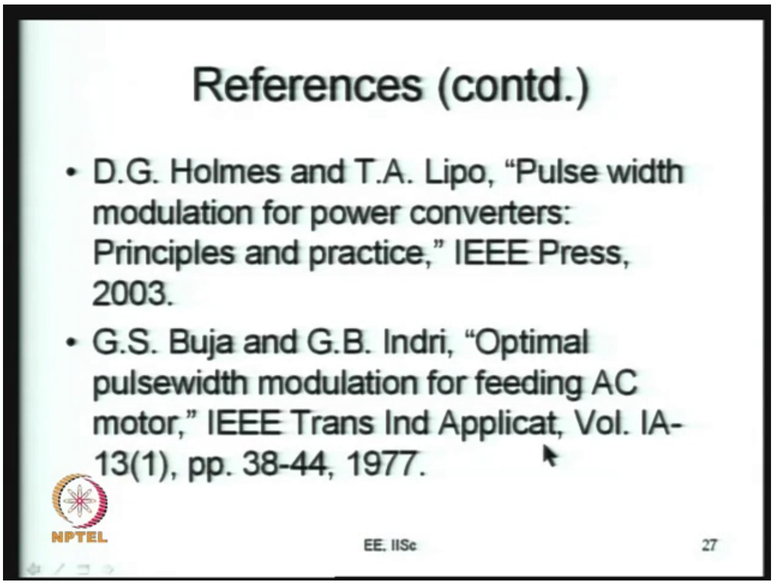

So, this is all you also have this book by professor Holmes and professor Lipo on pulse width modulation for power converters principles in practice this summarizes you know many of the selective harmonic elimination methods the work that have been done over the years has been consolidated, you will find lot of several graphs here which are very useful for you to understand you know what happens and things like this now.

So, this I would suggest this as an addition reading to now then about the optimal PWM, but minimization of THD this is a very good paper this is one of the first papers in this topic they calculate the switching angles in this paper Buja and Indri calculate the switching angles such that the THD is minimized or the weighted THD of the voltage is minimized this was published in the I triple e transactions is an industry applications in the year 1977.

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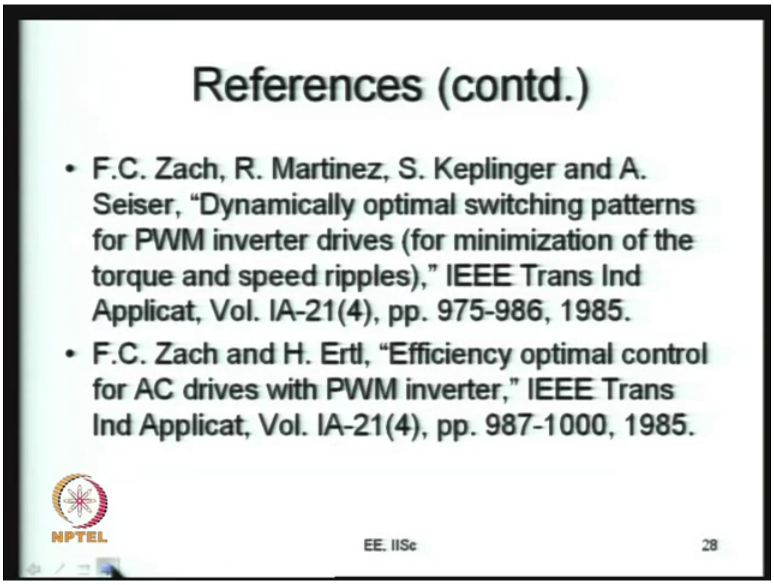

So, now you continue with that, not only minimizing THD you can also minimize the motors pulsating torque of the torque ripple and the speed ripple.

So, these paper by Zach Martinez and Kiplinger, Kiplinger and Seiser in the year 1985 on the same I triple e transactions and industry applications deals with that. How do you calculate a switching angles such that the pulsating torque is low that is what you know I just gave you an indication this paper discusses all the details there and similarly this is efficiency optimal PWM for ac drive. So, if they are trying to reduce the overall losses in the motor drive. So, the switching angles the losses are expressed are the efficiency of the motor drive is expressed as a function of switching angles and you try to optimize and get this.

So, these are certain very useful references that I would like to suggest. So, all these are examples of the stored waveform PWM method now. This is perhaps the last lecture that we will have an low frequency PWM methods in the low frequency we took it up essentially to understand what we are trying to you know get an essence of how fundamental voltage and harmonic voltages are affected by switching angles and so on so forth now. We are practically done with low voltage things and in generally you know we will dealt with selective harmonic elimination and always optimal PWM you save them as a PWM waveform do that now. From the next lecture onwards we will be looking at a situation where the switching frequency is much higher than the fundamental frequency, we will say probably the fundamental frequency is 50 hertz you may look at switching frequency of 5000 hertz or so, which is 100 times the fundamental frequency.

So, the way you analyze and all that could be very different when you are doing there now. So, that is what we going to look at now. So, most of the modern methods are really like that unless you go to very high power levels etcetera you will do this here. So, in the modern context there are certain low frequency cases where when the high when the power level is very high your switching frequency is low therefore, the ratio of switching frequencies the fundamental frequencies low and the other situation is the switching frequency is high, but the modulation frequency is also high in case of high speed motors that is again a situation where the low frequency methods we studied will be helpful. Next lecture onwards we will be focusing on the high frequency methods and thank you for your interest and hope that you will continue to follow these lectures.

Thank you very much.