Pulsewidth Modulation for Power Electronic Converters
Prof. G. Narayanan
Department of Electrical Engineering
Indian Institute of Science, Bangalore

Lecture - 17
Bus-clamping pulsewidth modulation

Welcome back to this lecture series on Pulsewidth Modulation for Power Electronic Converters. So, we have been discussing various pulsewidth modulation methods for power electronic converters after review on all power electronic converters such as DC; DC in AC DC in multilevel, etcetera, we are now been focusing on two-level voltage source inverters. So, we are looking at these power electronic converters now.

So, for voltage source inverters again we looked at many of these previous lectures, we looked at sinusoidal modulation we looked at first selective harmonic elimination and such low frequency techniques. And finally, you know over the last 2-3 classes, we have been looking at pulsewidth modulation which is assuming a fairly higher frequency that is if you have an inverter you know the inverter switches it switches at certain frequency which we call a switching frequency now.

So, the switching frequency is sometimes a low value that is I mean the ratio of switching frequency to the fundamental frequency is not very high, it may be 5, it may be 7, it maybe 9, it may be 15, it may be may be low number, other hand you know this switching frequency can be much higher than the maximum modulation frequency. And that is when you going for these power relation methods such as sine triangle PWM etcetera, now and we discuss sine triangle PWM and a few variants of that such as the third harmonic injection.

Today we will briefly review third harmonic injection and we will go on to these bus-clamping pulsewidth modulation methods now.

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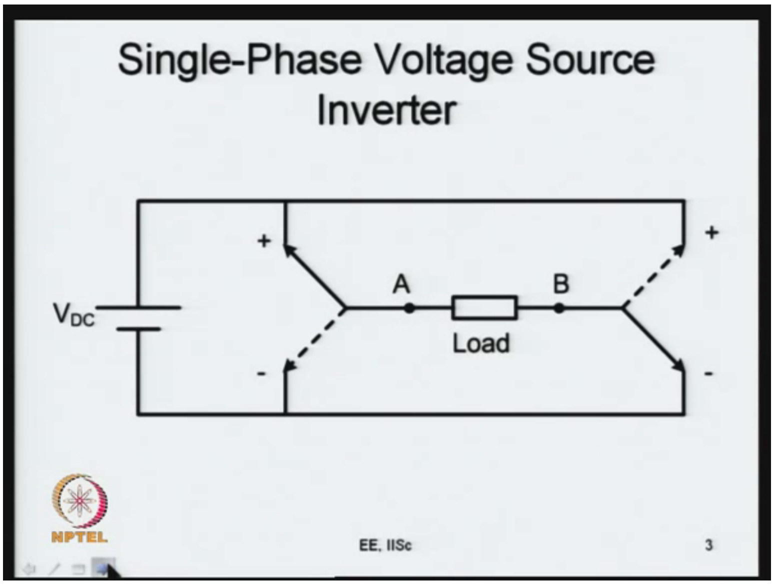

So, now here we have a single-phase voltage source inverter just to recap, it is a single pole double throw switch one leg and there is another leg and the poles are connected to the load terminals.

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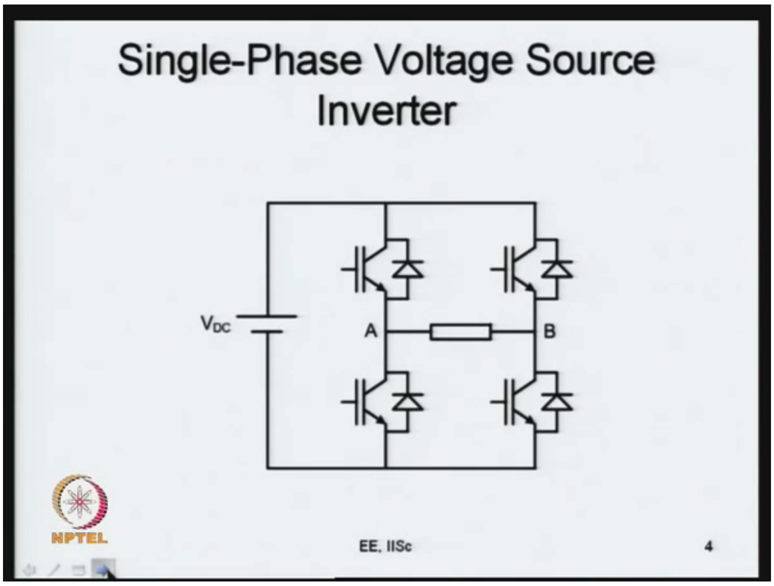

Then you have a single-phase voltage source inverter realized and you have this modulating and carrier signals going up and down like this.

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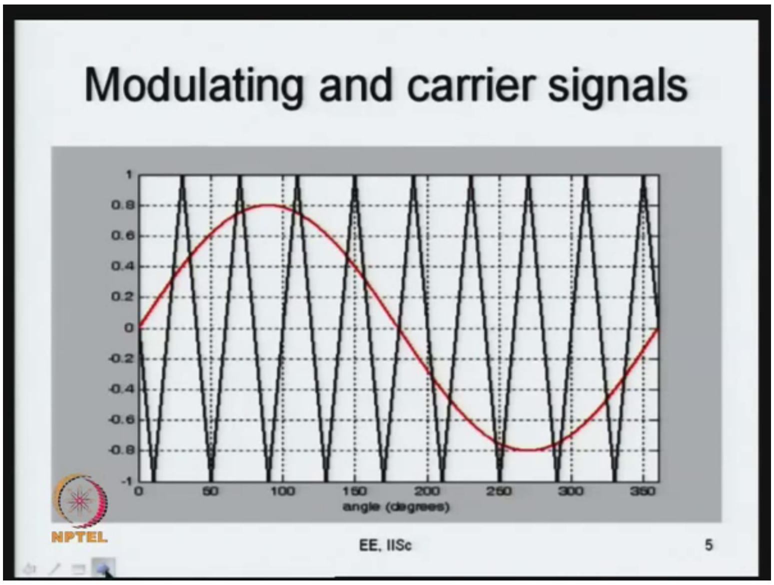

You have this unipolar PWM and second harmonic injection bus-clamping these are some of those which we had reviewed in the previous classes now.

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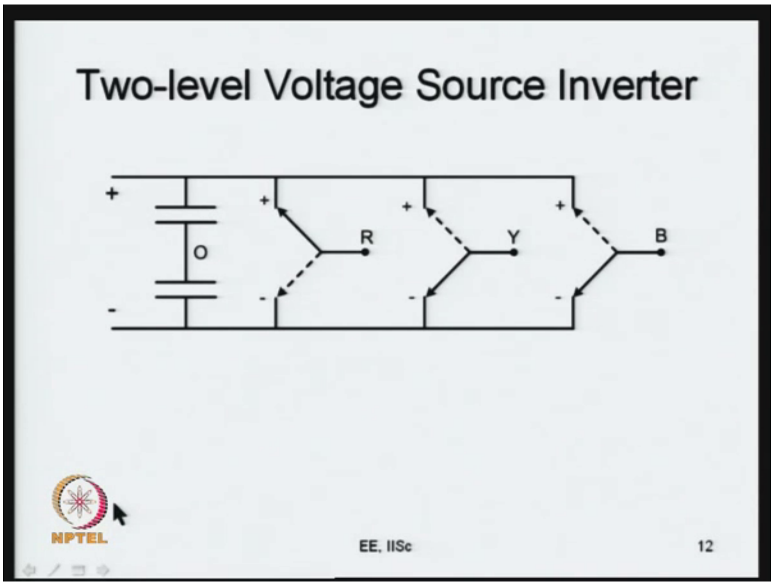

We if there is any requirement we can just go back and look at take a quick look at some of those now we have. So, let us just gets started with a particular point here.

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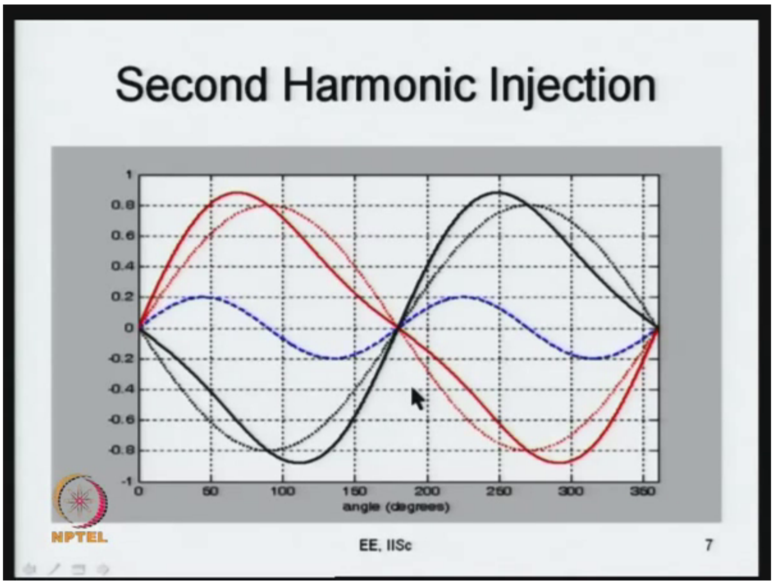

That is maybe you know we looked at second harmonic injection in the case of a single-phase inverter what do we do in a single-phase in in any inverter, we have a sinusoidal voltage and we have comparing in to the high frequency carrier now.

So, the idea here is the midpoint potential off that particular link measured with respect to the DC bus midpoint. So, this potential where is the average pol voltage what we call as the average pole voltage varies in a sinusoidal fashion.

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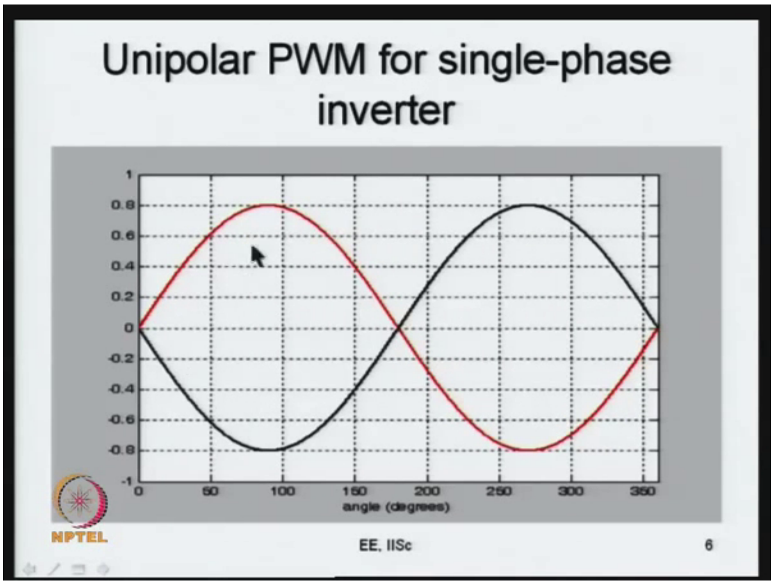

Now, you vary 2 average pole voltages now in a 2 phase inverter what did you do I mean in a 2 leg inverter which is meant for a single-phase inverter you vary; one of them in a sinusoidal fashion shown by the red curve you vary the average pole voltage of the other leg in this fashion as shown by the black curve and so, you get the difference between the 2 which is a sinusoidal function that is what gets applied there now.

So, here it is possible for you to inject a small amount of common mode voltage though there is no specific advantage in during that and there could possibly be certain disadvantages also maybe, but in a you know you can see that it is possible to add such a common mode voltage this blue thing is added both to the red sinusoid and also to the black sinusoid. So, that is a common mode component the resultant is this red discarded waveform which is basically the fundamental plus second harmonic and here also there is fundamental plus in the second harmonic now.

These second harmonics gets subtracted that is when you do a subtraction of this red curve. So, this is how the average pole voltage varies in one leg and like the black curve is how the average pole voltage varies in the other; if you take the difference between the 2 this what is common between the 2 that goes off and you get only a sinusoidal voltage at the output now.

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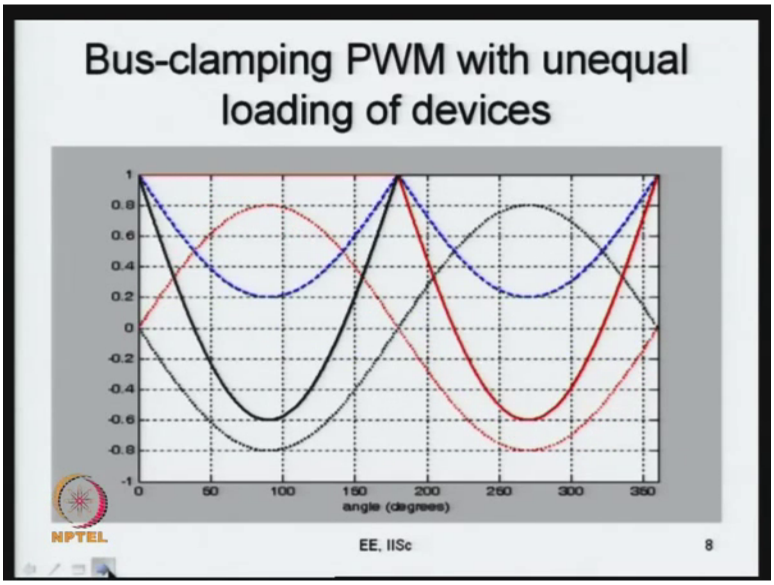

It is not very useful as an idea in single-phase inverters, but this is extremely helpful in a three-phase inverter as we would see as we have already seen also and briefly review today. So, sometimes you can add your common mode component as shown here. For example, that leads to bus-clamping that is what we saying is in this part the A leg is not switching here the A leg switching.

Therefore, similarly the B leg is not switching here and here it is switching here right. So, what is going to happen is in the as I was pointing out to earlier the A leg there is a top device is going to be conducting its going to suffer a greater amount of conduction last than the a bottom.

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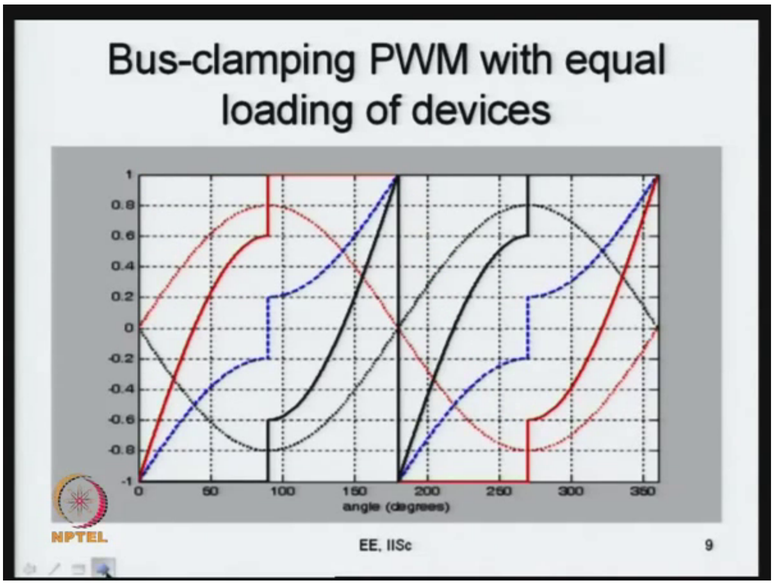

Similarly, here also the B top is going to conduct than the B bottom device. So, there is going to be unequal heating of the devices this is an objection now and we modified this and showed that you can probably think of some common mode injection component like this this common mode is obtained by subtracting the peak of the carrier from one of the modulating signals. So, for 190 degree it is one and another 90 degree you use the other signal. And by this you get a common mode component and this common mode component you add you get your red waveform there is one modulating signal the first 90 degree there is switching and the next 90 degree does not switch.

Similarly, the black waveform also has a 90 degree interval when it does not switch in every half cycle. So, here it is the top device may be conducting for a long time; here the bottom device would be conducting. So, you know it kind of balances out and you really do not have and you can also see that this common mode component has no average value. So, the top on the bottom devices are equal I mean their heating is equal their one is not heating much more than what the other is and so on.

And the same way the 2 legs are also. So, there are 4 devices and all the 4 devices are; they get heated up to roughly equal amounts of levels, now one of them gets heated up more than the other, then we know you are not utilizing the other one very well that is a between 2 devices; let us say top and bottom devices which are equally rated the top device gets heated more, but the bottom device does not get heated so much.

So, you are you have to stop what limits your usage the top device limits your usage how much power is being handled is limited by the top device. So, the bottom device is not fully utilized. So, that kind of a problem is not here.

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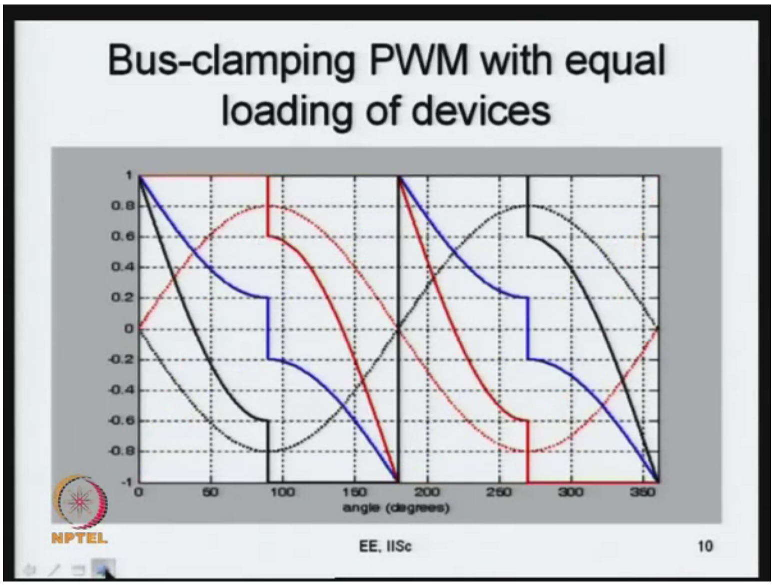

So, all the devices are equally loaded here we will deal with this when we calculate switching losses in a much greater fashion now.

This is another example of equal loading now. So, this is bus-clamping, now what we are going to do is this even harmonic injection has its counterpart third harmonic injection in the three-phase case which is what we are going to review and take it to a slightly greater extent and we are going to look at this bus-clamping methods for the 3 level inner three-phase inverter today now.

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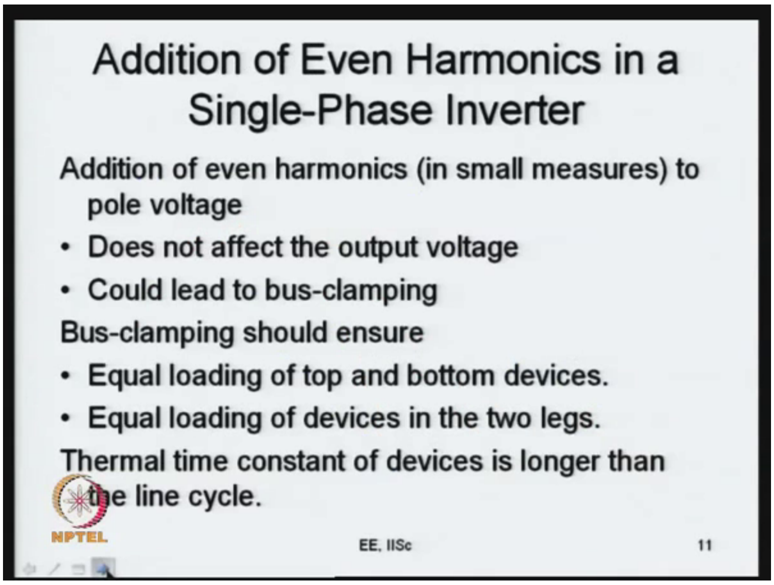

So, we made certain conclusions out of the additional even harmonics here which are therefore, you to see you add even harmonics and small measures to the pole voltage it does not affect the output voltage and it could lead to bus-clamping and this bus-clamping, but if you are doing bus-clamping then you should ensure that the top and the bottom devices are loaded equally and the 2 devices are loaded equally this bus-clamping can help you reduce certain amount of switching loss that is one of the purposes now and the heat reduces here the assumption is your thermal time constraint is much longer than the line cycle, because in some part of the line cycle, it gets one device gets heated more in some part, it gets heated less and it averages out and it averages out to a lower value than with the normal sinusoidal and modulation here the inherent assumption is the line cycle the is much shorter than the thermal time constraint.

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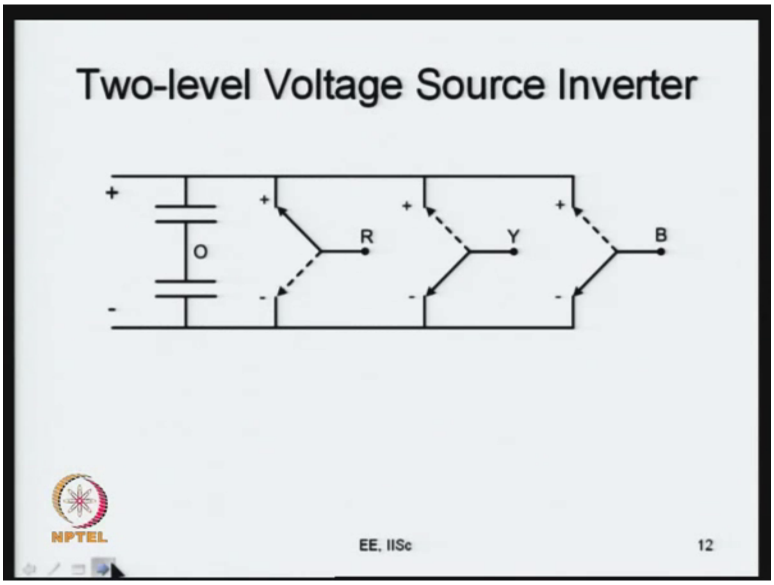

The same thing you go on to three-phase voltage source inverter the same 3 legs were there for you every leg represented as a single pole double throw switch move on.

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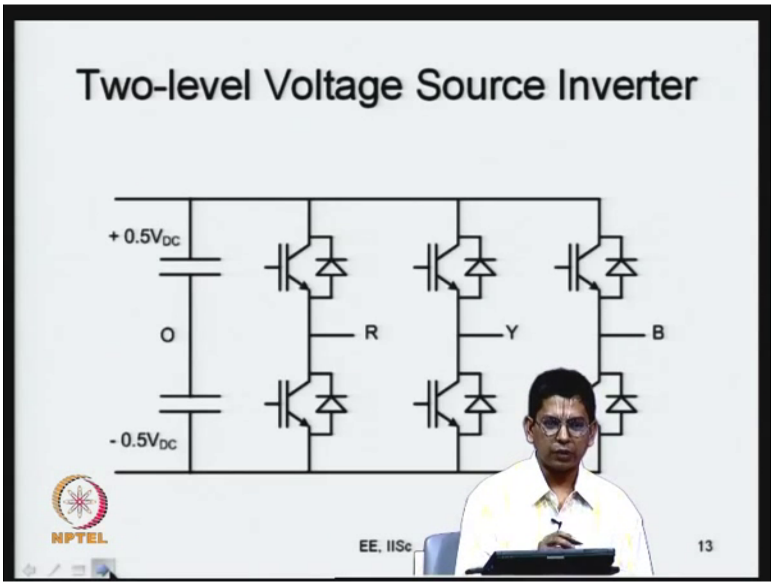

Now, what do you have every leg is represented in terms of 2 devices the top and the bottom devices which has switch in the complementary fashion we move on.

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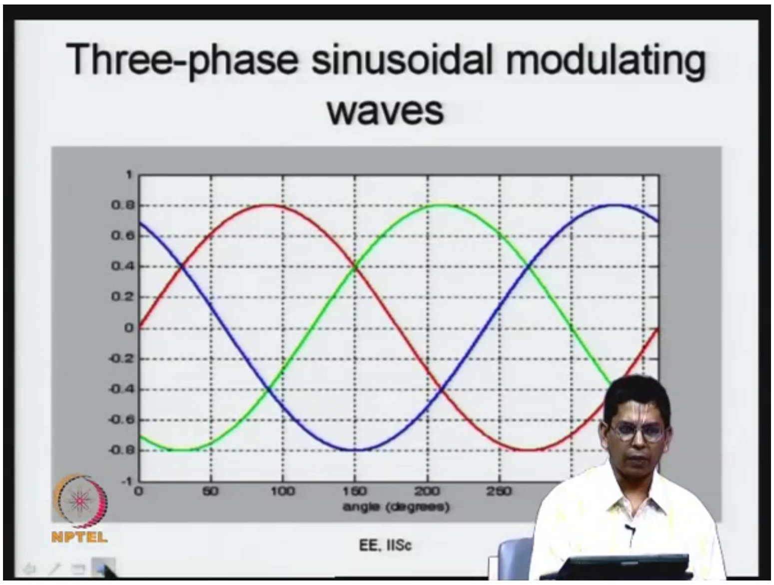

Now, these are the three-phase sinusoidal modulating waves just like a single-phase inverter that the; it has legs. So, you had 2 sinusoids there for the unipolar PWM and those 2 sinusoids were phase shifted by 180 degrees 180 is equal to 360 divided by 2.

Now, you have 3 legs. So, you have 3 sinusoidal wave forms all of the same amplitude same frequency and they are phase shifted by 120 degrees 360 divided by 3. So, that is what you have this you can compare with a common triangular carrier which can run up and down and up and down and up and down at a very high frequency and you switch the leg.

So, you switch whether a; from modulating signal is higher than the carrier of the top is on if it is lower it is the bottom is on that is the logic that we have been using. So, you move on. So, as I observed there are redundancies here this is what we have been saying the other day. So, what is that redundancy; now let us say as I pointed out the other day this is a carrier cycle.

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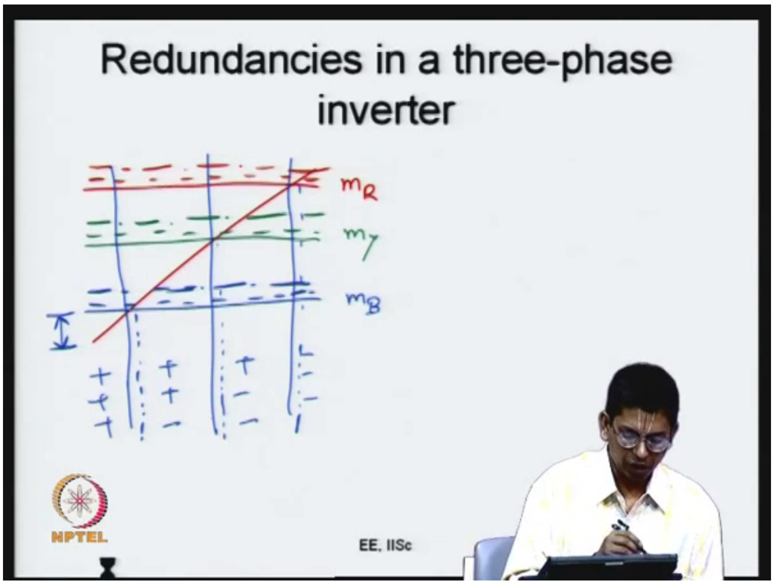

Now, we are looking at a carrier cycle the carrier cycle is much much smaller than the fundamental line cycle because it is much smaller than the fundamental line cycle; what happens your sinusoidal signals would look almost like a straight line. Now let me say this is your m R it looks like a horizontal line. Now let me just change the color to maybe green to represent the yellow

Now this could be your modulating signal corresponding to y phase; this is a sinusoidal signal, but the sinusoidal appears just as a horizontal line within this carrier cycle or you can consider a particular sample of that sinusoidal signal. Now let me indicate the blue signal also right this is m B. So, if I am considering sinusoidal modulation the three-phase waveforms are three-phase sinusoidal waveforms, then m R and m y and m B would add up to 0 if there is any common mode addition, then m R and m y and m B will not add up to 0, their average value will be equal to the common mode voltage now.

So, what we mean, but is redundancy is the load can be shorted either by all the top devices being on or all the bottom device is being on. So, here itself as we had observed the other day and repeating today you have the situation where all the 3 top devices are on and you have the extreme situation at the last interval where all the 3 bottom devices are on. So, if this is one interval this is other interval there the 2 intervening intervals during this interval what happens your red phase is now switched it is now plus plus and you mean your blue phase here the yellow phase y is switched now. So, it goes to plus minus minus now. So, this is how it goes now.

So, these are the 2 extreme states; now these are the 2 extreme states I am sorry you see this and you see this all the top are on here all the bottom are on here what happens to the load the load is shorted that is what it is. So, it does not matter. So, to the load, but it matters to the inverter because here the top devices are conducting here the bottom devices are conducting right.

So, these are called 0 states because the load voltage is short and it just prevailing these are called active stages because there is certain amount of power transfer between the DC set and the AC set during this intervals now and the line to line voltages are you will see pulses there in this case for example, R y will be 0 and y B will be a positive pulse and B R will be negative DC pulse. Again if you look at this interval, you will find that the R y is the positive y B will be 0 and B R will be negative pulse that is what you will see whereas, if you look at these 2 intervals V R, V y and V B will all be equal to 0 right.

Now, by redundancy we mean here also it is shorted and here also it is shorted, here it is shorted by one switching state, here it is short by another switching state. So, the inverter has 2 switching stage which both result in shorting of the load. So, this is what we mean by redundancy; now how is this useful you see that as we told earlier you know if the there is a small common mode component is added now let me just go on to the red one.

Now, let me say I shift the red signal slightly above, I shift the red signal slightly above what I may going to with the yellow signal; now which I am representing it in green here this also I am shifting slightly above to the same extent there are drawing inaccuracies, but please be aware that I am shifting both of them up by the same extent, right.

Now, let me go on to the blue signal correct right here also I am shifting all of them to the same extent; that means, I am adding a common mode signal to all the 3 of them. Now what is the result of this common mode addition because of this the red signal has been shifted what has happened here the red m R and the carrier intersect, but the intersect at a later time. So, you start from here the red I mean the carrier is the same and the first intersection occurs in the blue m B and m B is now shifted above. Therefore, what happens this switching instant slightly changes, it is not this previous instant shown in thick line it is the one that is shown in the discontinuous dotted line. Then the next time it intersects it with carrier intersects with m y that instant is again shifted by how much is it shifted again it is shifted to the right it is shifted by the same extent correct then what happens to the m R; m R is also shifted up because of which you have the same situation now.

So, all the 3 switching instances are now shifted to the right and by the same extent; if my addition here is not positive, if it were a negative common mode component, all of them would have shifted left now, but what do you find now since this switching instant is now shifted to the right, excuse me, I will pick up this arrow this switching instant is shifted to the right, this is again to the right now right. So, what is happening there effective interval for which the active shed is applied is not changing again the effective interval for this this active state is applied is not changing, but the interval for which this 0 state is applied as increased and at whose expense at the expense off the time for which this 0 state is applied.

So, once again that time for which these 2 0 states are applied together is not different individually they are different. Now the sum of these 2 is not the same is different. Now this is what common mode addition results you add small amount of common mode the one of the 0 state time decreases at the cost of the other. So, as an extreme case if you if you if I add my m R. Now let me go back and pick up the red thing again, now let us say I add it in such a fashion that my red signal becomes equal to the peak similarly I shift all m y and m B above. Now what could happen R phase will be clamped R phase wont switched at all?

So, it is the redundancy of the inverter which allows me to add a common mode component and I can add a common mode component such that one of the phases is switched. Now let me complete this by indicating what happens to the green also if you add further the green will also go up like this and what will happen to the blue this will also go up like this. So, all the 3 have gone up now m R has gone and hit peak; peak of the triangle; therefore, there is no intersection it does not compare m R this is always high R phase top device is always high.

So, R phases is clamped where is it clamped, it is clamped the positive DC bus and therefore, you call it bus-clamping other thing that you can do is to add a negative common mode component and how big can the negative component be it can be. So, big the negative component can be as high as this and of course, in the negative direction. So, if you had a negative component equal to the difference between minus VP that is the negative carrier peak and m B. Then m B will come and hit the negative limit m y will come down m R will also come down, but m B comes and hits a negative limit again there is no intersection between the carrier and m B. Now, m B is always lower than the carrier in that case; that means, the B phase bottom device will always be on and B phase, it is always connected this clamped B phase does not switch it is clamped it is clamped to what it is clamped to the negative DC bus.

So, when you have a situation like this when m R is greater than m y greater than m B, it is possible for you to clamp R phase to the positive bus or it is possible for you to clamp the B phase to the negative bus.

So, you try to do one or the other of this. So, the same thing one thing is possible do is since you do it for switching loss you can see which of the 2 phases carry higher current whether R phase carries higher current or the B phase carries a higher current. So, whichever carries higher current you can go on clamped that is one commonsense way of doing it now, but what I would like to say is there are many modulation techniques which have come out of this possibility which is what we have been discussing now.

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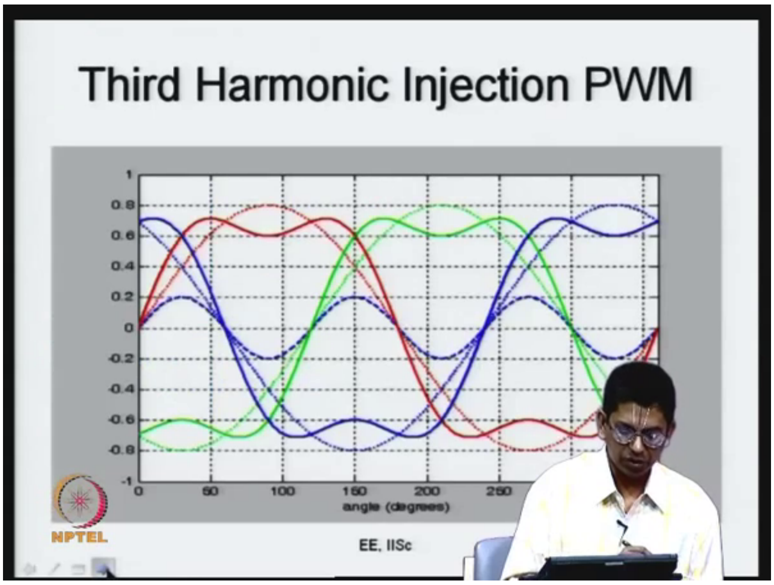

So, one of them is about this third harmonic injection where you are adding a third harmonic component to the prancing wave we also discussed it earlier.

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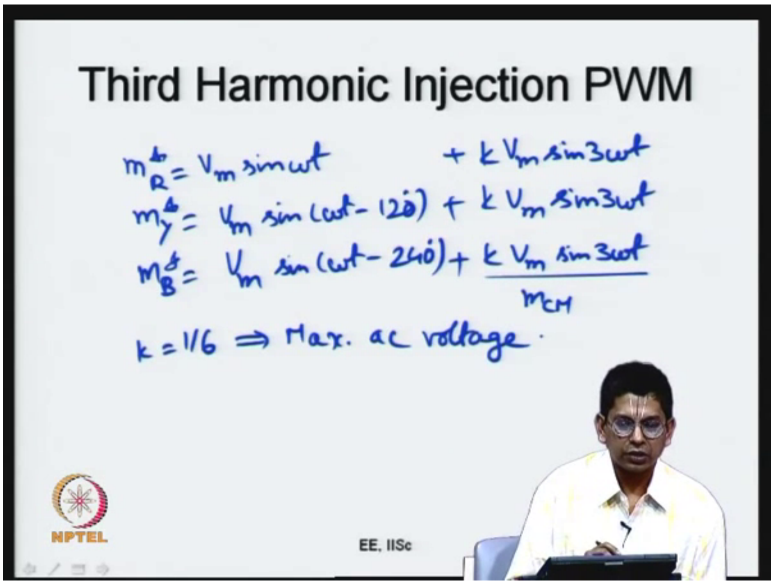

Now, if I write down the equations further you have m R; m R is going to be V m sin omega t this is what it is in a sinusoidal modulation m y is sin of omega t minus 120 and m B is V m times sin of omega t minus 240; this is what is in the case of sinusoidal modulation how different is third harmonic injection you add certain common mode component to all the 3 and call that as m R star, m y star and m B.

What is the common mode component you take it as some V m sin omega t a fraction of that k a times V m sin omega t, here also you add the I am sorry this is k times V m sin of 3 omega t this is a third harmonic component and what is its amplitude it is a fraction of V m; now this fraction can be 0.05, 0.1, 0.16; so on like that. So, this is also the same k times V m sin 3 omega d here also the; it is the k V m sin 3 omega t. So, this is what is called as the common mode component this is what is called as the common mode component the common mode component is a third harmonic, it is a natural thing if you had a third harmonic to the sin and phase shift is m R stare by 120 degree, you will get m y star.

Now, the third harmonic phase shifting by 120 degree for the third harmonic is one cycle now if you subtract m R stare minus m y stare the third harmonic components will go away from that to you get this kind of; so, this is third harmonic injection and different values of k are possible. Now last time we saw k is equal to 1 by 6 we saw this k is equal to 1 by 6 and this k is equal to 1 by 6 gives you maximum AC voltage with the given DC bulbs voltage I have this thing with me I can show this to you. So, this is what is k is equal to 1 by 6 now.

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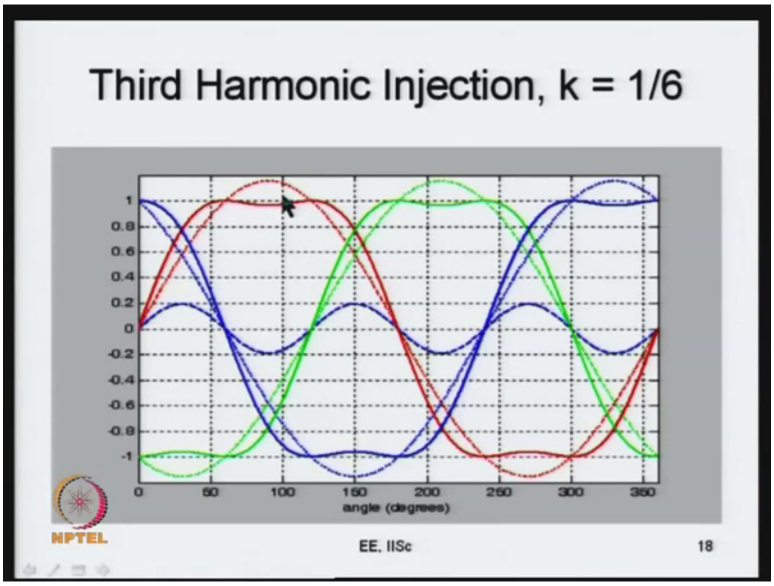

Now what I have here the original sine wave, this original sine wave the red dotted line that is now I have drawn it for m is equal to 2 by root 3 it is 2 by root 3 times V peak 2 by root 3 is roughly 1.15; it is 1.15 times V P. Now with that when I add one sixth amplitude third harmonic component it is like this now. So, this amplitude is 1.15 divided by 6 is something like point 2 little lower than point 2 that is what you find here now when I added this common mode to all the 3 what I am getting here is the sine function the modulating signal its head goes down a little bit head bends down little. So, it is tough this it is coming down like this and here again it goes down this like now.

So, what happens now this is my peak earlier if I consider the original sine wave the original sine wave was greater than the peak of the triangle there was no comparison between the triangle and this thing. So, the top device will always be on in such kind of situation that would be called over modulation that is not sinusoidal modulation it will introduce lots of distortion in the current. Now, because the average pole voltage would not be a sinusoidal signal how would the average pole voltage would be if I take the dotted red line and compare with triangle and switch my inverter the average pole voltage would vary like this as per this dotted line up to this point, but it cannot go above that, because the average pole voltage gone cannot go above VDC by 2 VDC by 2 is the maximum limit when the top device is fully on. So, it gets clipped like that it would get clipped and then it would come down like this now.

So, you apply a sinusoidal voltage, but your average pole voltage is not sinusoidal actually your average sings sinusoidal will be a clipped sine wave here also it will be a clipped sine wave the same thing it will be in the B phase and R y phase and B phase also.

Now if you have added the third harmonic component what has happened is though the peak of the sin is 1.15 or so, the peak of the modulating signal is just one. So, it does not go beyond that and now this is your average pole voltage this is your average pole voltage you can see that it is always within a limit of VDC by 2 and what is your y phase average pole voltage as shown by this green curve with a bent head here and B phase average pole voltage it is like this now what is going to be R to y average line to line voltage it is the average pole voltage of R phase minus average pole voltage of y phase when you subtract these 2 the common mode component given by this blue dotted signal will go dash will go and what you will get is only pure sinusoidal waveform.

So, you can get without resorting to pulse trapping or over modulation you can extend your voltage you can get more 15 percent more line voltage because you know this is up to 15 percent more now. So, that is what is this an advantage and k is equal to 1 by 6 has been found to be the optimal value, I will just tell you a little later how to find out this optimal value formally, but this is been found to be the optimal value that gives you the highest value of AC side voltage for a given DC bus voltage. Now let us say you have a DC bus voltage let us say it is 600 volts and you want the maximum line side voltage possible without going into over modulation then what you need to do is you have to take and you want to do third harmonic injection then the amplitude of third harmonic that if you inject should be one sixth of the amplitude of the fundamental.

Another variant of this is I have given as k is equal to 1 by 4 here one fourth of the amplitude is added now I have taken a fundamental component I am shown that to be something like one point one until in one point when I am adding a sin component like before this is a third harmonic sine wave and how is this third harmonics sine wave this third harmonic sine wave is one fourth the amplitude of the top now.

When I am adding this once again I am getting the head is coming down. Now you can actually see there are differences between these 2 you see; here it is somewhere the peaks are occurring somewhere close to 60 degrees.

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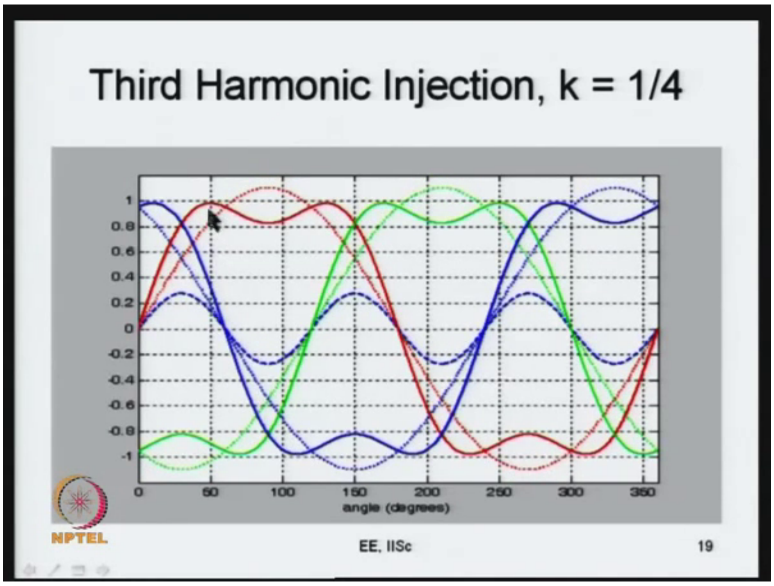

So, and here you see the peak of the waveforms are occurring a little further from those angles now.

So, depending on what percentage of third harmonic you add the where exactly peak occurs changes a little there is some difference it makes. So, what this specialty of 1 by 4 you can actually add 1 by 8, also 1 by 7 or so anything k you can choose to be anything within a small number within a within a small range you know that is all. So, the resultant waveform should not go above that is one reason, now k equals 1 by 4 has been found to be optimal in terms of harmonic distortion what do you mean by that when I use this modulating signal that sinusoidal signal and add 1 by fourth amplitude I get the resultant modulating signal I do the modulation.

Now, I will get some harmonic distortion I will get certain amount of RMS current in ripple current in my line currents that is lower for k equals 1 by 4 than it is 4 k equals 1 by 8 and k equals 1 by 6. So, it has been found to be optimal that what really it does there is internally it divides these 2 0 state times equally plus plus plus and minus minus minus it makes the more or less equal that is what it does this is what an another technical conventional space vector c does and much more naturally which we will see when we start space vector based modulation. And it is also possible to get this closer, but one thing that I just want to point out is the choice of k you go in for one common choice of k is 1 by 6 which will give you the highest line side voltage and k equal 1 by 4 which will give you the best harmonic distortion.

In fact, conventional space vector PWM as we will see combines the advantages of both it would give a thd as low as that tough this k is equal to 1 by 4 and a AC side voltage as high as that of 1 by k equals 1 by 6, you will see that a little later in 1 or 2 lectures later now,

So, regarding third harmonic injection the points that I would like to say here is now you have this.

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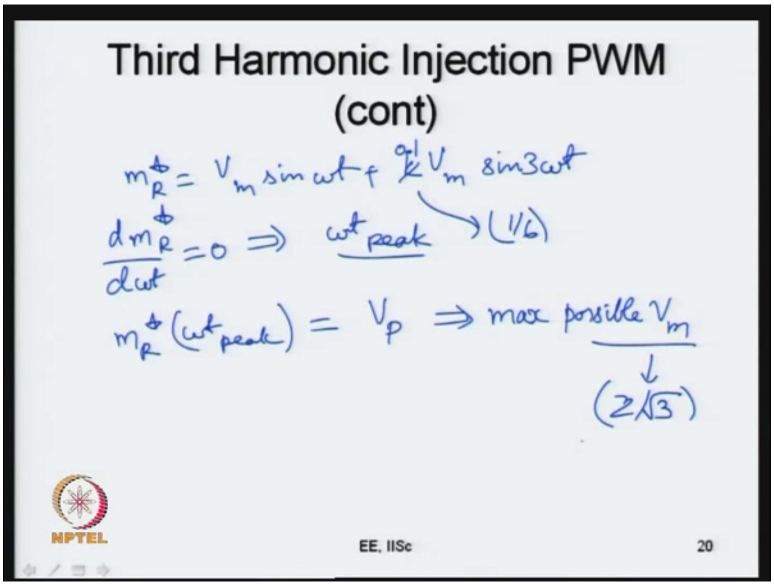

Now, you have your m R star is equal to V m sin omega t plus you have k times V m sin 3 omega t. So, what this k can be is another issue now. So, as found as I told you the waveform peak occurs at different places. So, now, you see this is how they have the peak occurs here in this waveform you can see that the peak occurs here and here its symmetric, but the angle at which it occurs it looks to be a you know it is 50 degrees, it is somewhere around 50 degrees; now where as in the previous case it looks to be around 60 degrees.

So, where the peak occurs is different now how can you find out where the peak occurs simple as you would all know all that you need to do is you do this d m R star upon d omega t and equate it to 0 if you do this you will get omega t peak you will get the instant at which this is the m R star has a peak value let us call that instant as omega t peak. So, this is once you have this omega t peak.

So, at omega t peak you can say that m R star at omega t peak what is its maximum value this maximum value can be all the way up to V P. So, this will give you, this will tell you how much is that maximum possible V m, this will give you the maximum possible V m for a particular value of k for example, let me say I take this case point one and I go doing about this analysis I say point one sin omega t what do I do d by d omega d m R star is equal to 0 that would give me the omega t peak theta peak the instant at which my function goes to a maximum value. So, that will happen twice one the in the positive of cycle it will happen in the first quarter cycle and also it will happen at the next quarter cycle now.

So, I can find out this instant omega t P, I can find out this instant omega t peak right once I find out that instant omega t P, I can say that that is the highest value of m R star that can go as high as VP, it cannot go beyond that, but it can go as high as V P. So, when I equate that it is the maximum value that I will get whatever is the maximum possible value of V m for that particular k. So, you will see that if you take your k to be 1 by 6, then this maximum possible V m will turn out to be 2 by root 3 for all the other cases it will be somewhere between 1 and 2 by root 3 this is 2 by root 3 it is not very clear it is something like 2 by root 3 what you might have known that is the maximum possible with k is equal to 1 by 6 if you go to k is equals 1 by 4 you will get a number which is lower than 2 by root 3 right. So, this is about third harmonic injection.

And let us go into the bus-clamping PWM as I said in the third harmonic injection and the bus-clamping third harmonic you are adding a third harmonic component right.

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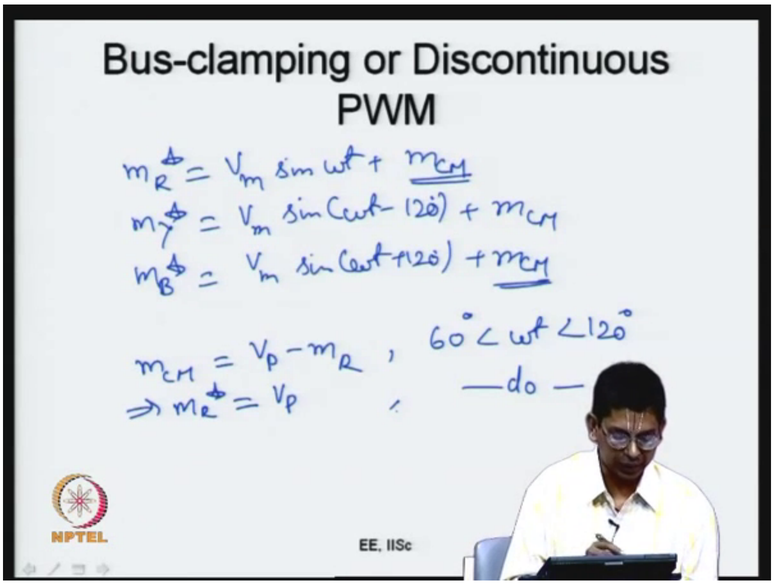

That is you are adding m R star this is V m sin omega t is the original m R plus you are adding a common mode component again for m y star also you do the same thing this is V m sin of omega t minus 120 plus the same common mode component is there m B star is equal to V m sin of omega t plus 120 plus this common mode component.

Now, what is this common mode component is the question in the case of third harmonic injection the common mode component was a third harmonic component V m sin omega t can k times V m sin omega t now you can choose an m c M such that it would clamp the bus it; it would clamp one of the phases now for example, let me take this can I clamp R phase yes I can clamp R phase when can I clamp R phase. Now to which bus it could be its a positive bus or negative bus when can clamp it to the positive bus when out of the 3 signals m R star m y star and m B star R m m y and m B. These are m R m y and m B out of the 3 sinusoidal signals when m R happens to be the most positive signal then it is possible for me to clamp R phase to the positive bus similarly if m R turns out to be the most negative signal out of these 3 then I could possibly clamp R phase to the negative.

So, how can I clamp m R star to the positive bus now let us say m R star V m sin omega t let us take omega t is equal to 90 degrees or something very close to that. So, this is equal to V m m R is equal to V m V m plus m c M. So, you want it to clamp. So, what do you do you must take the difference between V peak and m R you take the difference between V peak and m R now for example, I can say m c M is equal to V peak minus m R when in the region let us say 60 less than omega t less than 120 this is when R phase goes to the peak at 90 degrees, it goes to the peak between 60 2 9 120; it is the most positive of the 3 sinusoidal modulating signals.

So, you can pick up m R subprime VP; VP minus m R you can treat this is the common mode signal if you had the common mode signal to all the 3 quantities what will happen your m R star this would imply your m R star is equal to VP when in this range in this range. So, in the next thing between 120 to 180 you will pick the next phase and 180 to 40 you will pick.

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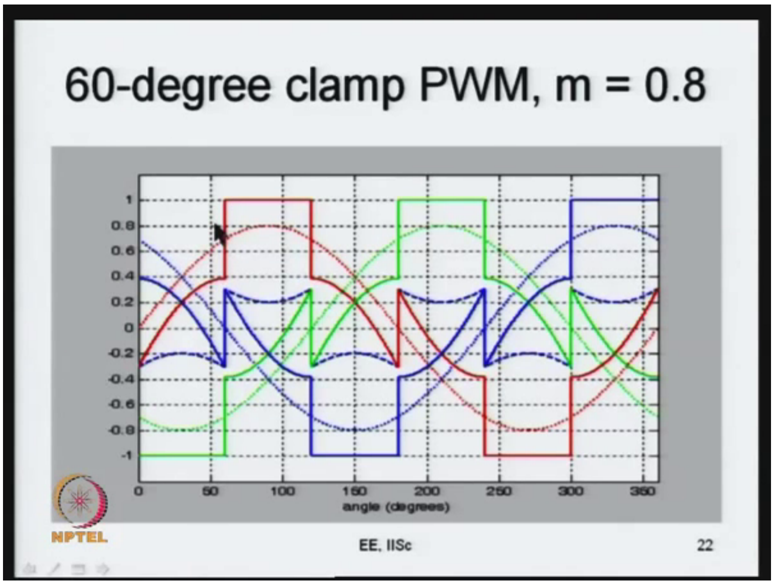

The next phase that is how get one of the first bus-clamping PWM method which we call as a 60 degree clamping method.

Now, you can see that this is as I pointed out earlier R phase has been clamped here because how is the common mode been derived the common mode has been derived as the difference between VP and m r. So, this is the common mode signal law now the next time what I am doing this is the common mode signal the B phase is getting clamped now how is the common mode been derived as the difference between minus VP and the B phases sinusoidal signal that is the common mode component here. And again see you see the common mode component goes to like this and you can see that the common mode component is a triple frequency component the fundamental frequency of the component is now if you look at it see this is 60 degrees this is 100, another 60 degrees. So, from here to here is one 120 degrees now.

So, this common mode component has a fundamental frequency that is equal to 3 times the fundamental frequency. So, it is a triplet it has all tripling frequency components, it has third harmonic not only third harmonic it has ninth harmonic; it has 15 harmonic it has twenty first harmonic and it has all of them it has only odd harmonics in this case you know because they are only these there is half wave symmetry here is has only third ninth 15; twenty first term all these harmonics it really has and goes on the class it goes on. So, you are adding them.

Now, if you once you add you get this resultant signal this is your red phase signal and what is your yellow phase signal shown by the green line here. So, both of them have the original sinusoid plus the common mode added. So, your red phase pole voltage the midpoint average pole voltage measured with respect to the DC bus neutral has this wave shape shown by the red modulating signal the yellow phase has again the wave shape shown by the green modulating signal right the difference between the 2 is only a sinusoidal signal. So, what gets applied as VRY the average voltage of VRY will be a sinusoidal signal this is not be there now.

So, this is where you call it bus-clamping because R phases is clamped to the positive bus here B phases clamped to the negative bus y phases clamped to the positive bus R phases clamped to the negative bus and it goes on like that; now we call it 60 degree clamp why because it is clamped in the middle 60 degree duration it is just a name that we are giving you also find various other names available in the literature because it is clamped for the middle 60 degree duration in every half cycle. Now in the posture of cycle it is clamped to the positive DC bus in the middle 6 duration in the negative half cycle for the middle 60 degree duration, it is clamped to the negative bus. So, we just give a name called 60 degree clamp in this course for this now.

So, this is one possible clamp not all possibility now and also the other name given is a discontinuous modulation with discontinuous PWM is more commonly used here why is it called discontinuous PWM if you look at the modulating signal this is the modulating signal. Now this modulating the original sine wave there is a continuous function of time it has sin omega t, it is a continuous function of time.

But the common mode that you are adding you say discontinuous function of time and the some of these two which is the actual modulating function is a discontinuous function of time you see there is a discontinuity here you see there is a discontinuity here you see there is a discontinued here there is a discontinuity once in every 60 degrees in this particular case because of this discontinuities, it is called a discontinuous modulation scheme or you know discontinuous PWM is the other term used for bus-clamping PWM.

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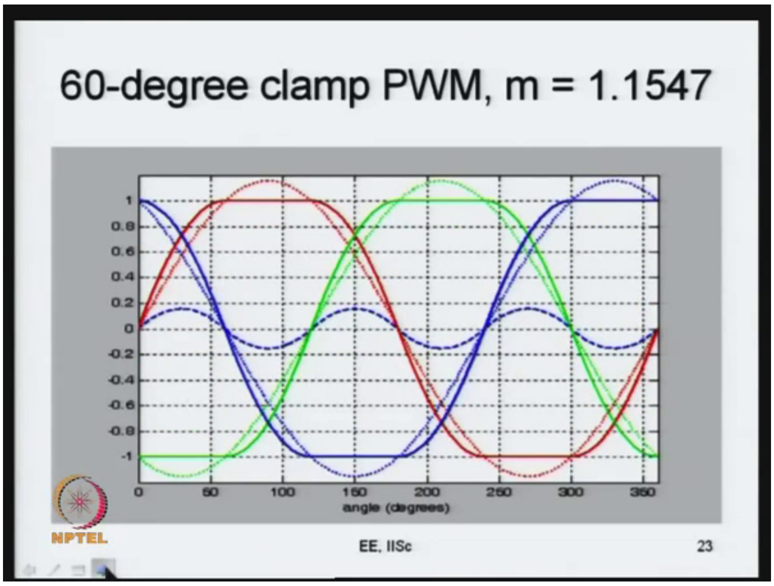

Now, the same 60 degree PWM as I was saying what would be the advantage one of the advantage we have already said which I am repeating is now the peak it goes how much does it touch now I have taken a peek now high is that it is 1.15 that is 2 by root 3 as I has I considered for the t h a PWM with k is equal to 1 by 6.

So, now what is happening you see that in this signal looks qualitatively different as the fundamental peak goes on increasing what will happen is this sine will come down come down and when the fundamental cross is one this will look different the common mode component will look very different like shown here now this is a case where it is the highest possible fundamental voltage I have drawn. Now you see that for this, this is the common mode component when I add the common mode component what happens is wave form goes between 60 to 120, it is still clamped and then it is down it this part is not sinusoidal this is dotted line is sinusoidal, but the solid line is not sinusoidal and here it is flat and here what is the difference between the dotted line and this this sine this wave which is sin looking wave it is not really a sine wave, this is the difference of sin omega t minus one that is I mean one point one phase sin omega t minus one is what it is now. So, you have this wave form and you had this stuff.

So, you are able to accommodate a sign where up to 2 by root 3 that is 1.1547. So, you get 15 percent more fundamental voltage that is one of the advantages as I as in the third harmonic injection with k equals 1 by 6 the other advantage you can get is of course, you are not switching you are not switching for one third of the cycle therefore, the switching loss can be reduced now and the conduction loss here you see the positive device will take more amount of heating that is will get heated more because of continuous conduction the same way the bottom device in that R phase leg will conduct continuously here and will get heated up. So, they get heated to an equal extent if you look over a fundamental cycle they get heated to an equal extent now.

So, it is distributed again here the assumption is the line frequency the line cycle is much shorter than the thermal time constant. So, it takes a long while for the heat to get distributed. So, you have this kind of an assumption here you have these waveforms. So, one advantage is that you have you can get a higher fundamental voltage another advantages you can possibly reduce the switching loss, but if you see the switching loss can be considerably reduced only if the phase current also has its peak in this side if the R phase current also has its peak in this region if R phase current is going through a 0 crossing here not much saving is obtained an R phase for example, has its peak here then R phases switching not much is obtained here.

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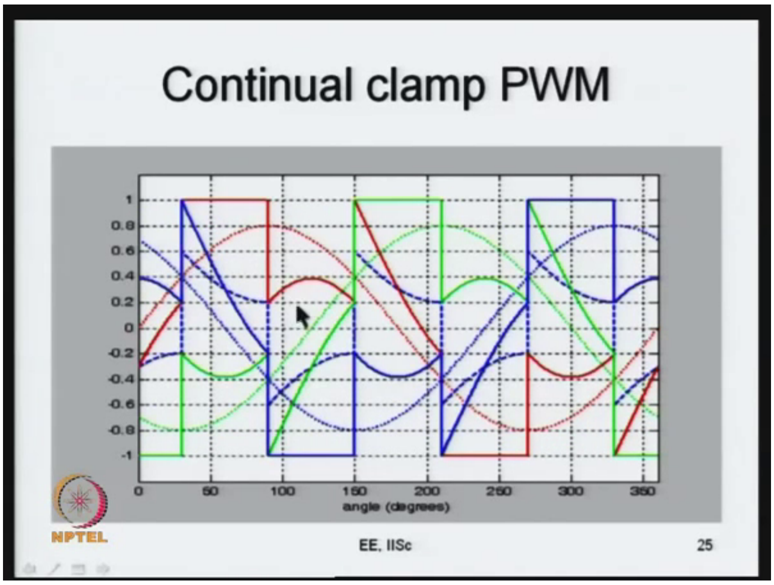

So, you have this thing of phase shifting which you can normally do. Now, for example, if the R phase in this case let us say it is leading the current is a little leading then you can go in for a clamping as shown here now. So, this part can be clamped here also it is clamped for 60 degree duration for continually your clamping.

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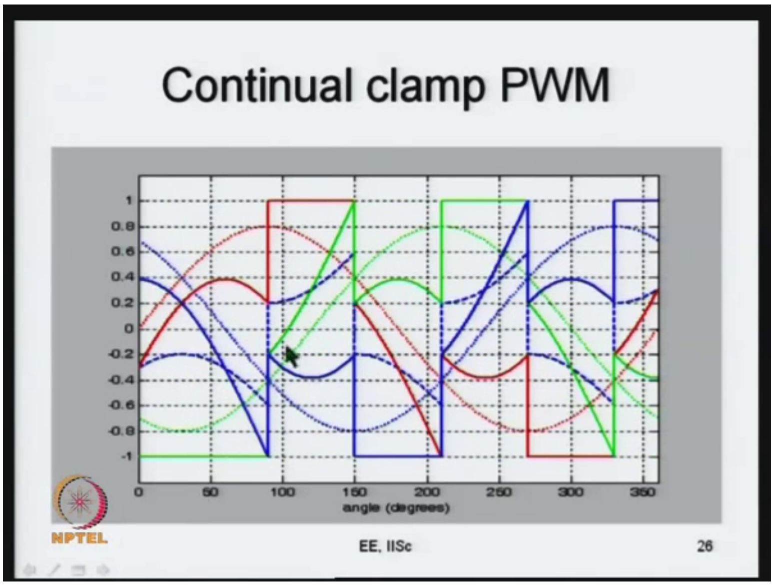

So, the phase leading in case the phase is lagging you can clamp like this where you can see that here in this case the R phase is clamped between 90 degree and 150 degree now. So, this is another example of what we call as continual clamp PWM why do we call it continual clamp PWM in all these cases in all these cases from here or here this is the same thing or here or here a phase is getting clamped continually for a 60 degree duration that is what you can clamp it for if you clamp it for 120 degree duration there will be an uneven loading on the top and bottom devices it is clamped continually alternatively this 60 degree duration can be split into 2 parts and that is what we would call as split clamp PWM in the next few slides now.

So, this is continual clamp PWM when the clamping can be for 60 degree duration, the 60 degree duration can start as early as 30 degrees and end with 90 degrees as it can start at 40 and end with 100 and 100 degrees; 50 to 110 the other extreme is 90 to 150 degrees. So, anywhere between 30 to 150 you can place this 60 degree interval and it is not symmetrical in all the phases now.

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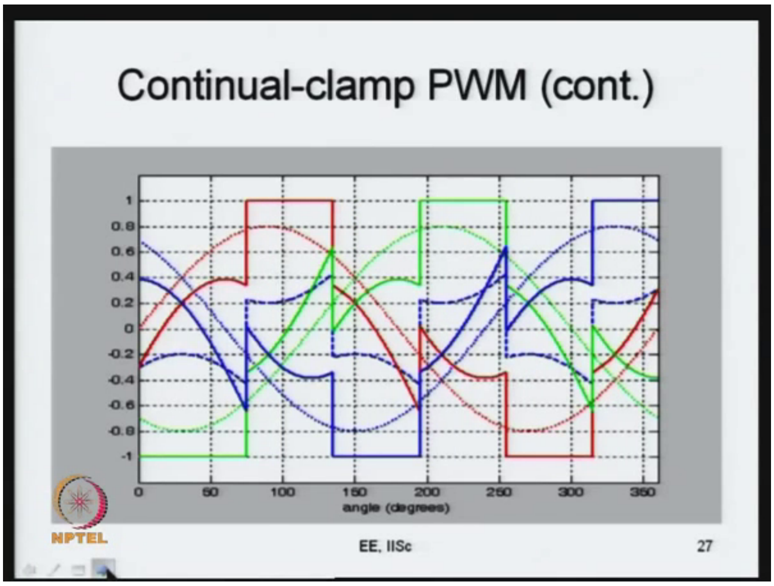

So, these are some examples of continuous clamp PWM that I have given here now. So, you have all these examples of that it is clamped as it goes now.

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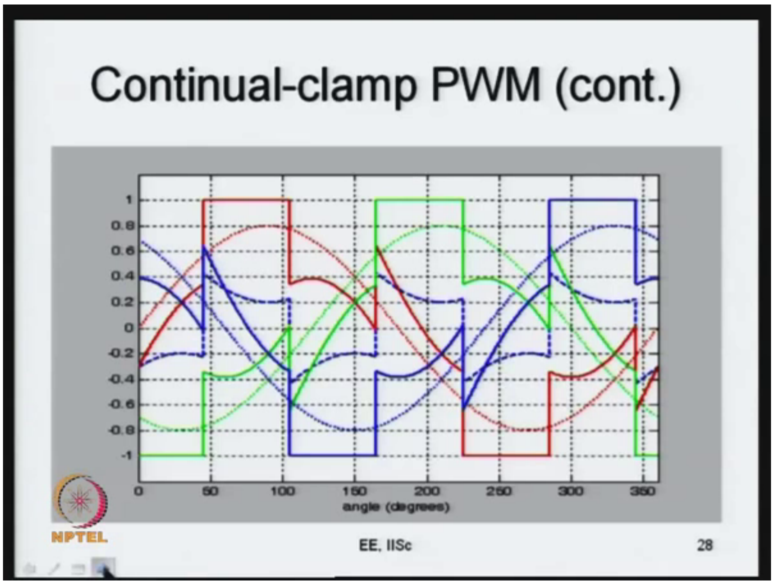

So, the other thing is if you want to break it the continuous 60 degree clamp duration can be broken into 2 parts what I am calling as 30 degree clamp here.

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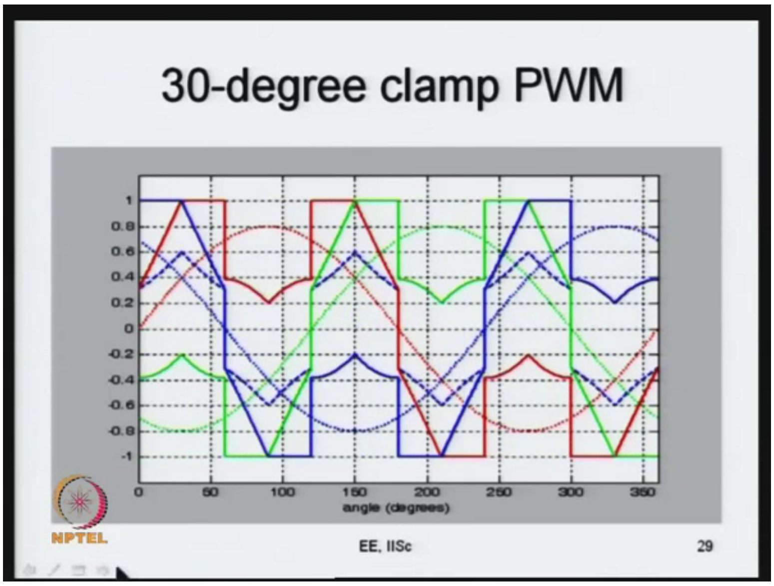

If you see here this phase is clamped the R phase is clamped here what is the kind of modulating signal the modulating signal is this blue signal going up and down and there is a discontinuity here and down and up there is a discontinuity here then up and down and then there is a discontinuity here then down and up discontinuity here this is the nature of the modulating signal this modulating signal if you add to this you get that R phase is clamped for 30 degrees here between 30 to 60 degrees

And here again it is clamped for 120 to 150 degree. So, this 30 to 60 is the middle 30 degree duration in the first quarter cycle again this 120 to 150 is the middle 30 degree duration in the next quarter cycle. So, every phases clamped for 30 degree duration in the middle of every quarter cycle and that is the way we give a name called 30 degree clamp PWM. Again this is only name there are different names are used for these methods and we call it 30 degree clamp PWM because every phases clamped this way the middle 30 degree in very one of this now.

So, this 30 degree clamp is a special case of split clamp PWM that is what has not commonly been realized. In fact, it is not you know the 60 degree duration has been broken into 30 plus 30 should it be broken only a 30 plus 30 it can it not be broken as 45 plus 15 or can it not be broken as 15 plus 45, yes, it can be done and the more general cases what we would call as split clamp PWM.

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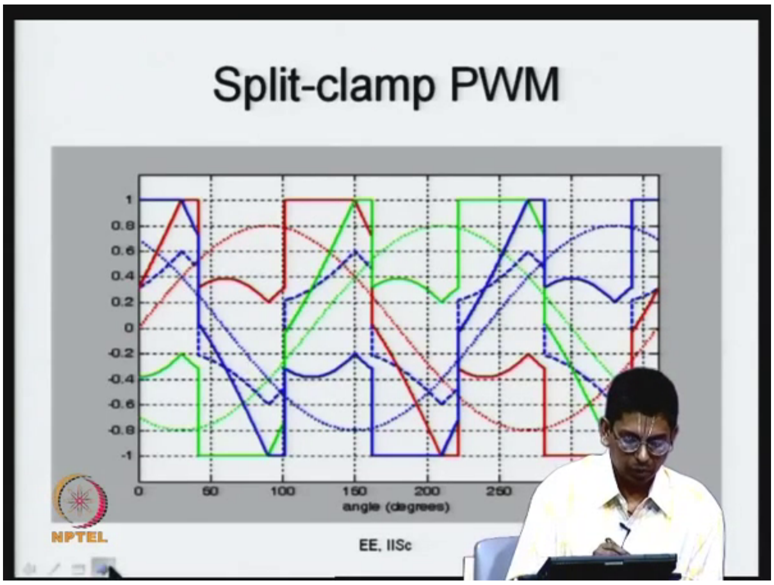

Now, this is an example where you start clamping again at 30 degrees, but this is not going all the way to 60 degrees here its stops at 42 degrees or 45 degrees or something like that 42 degrees may be and the remaining duration let us say if you have clamp for twelve degrees here. So, the remaining 40 degrees you clamp it here it is a little difficult to see this possibility, but this possibility exists and there is not been thoroughly discussed its only in a very few recent papers you find this possibility kind of getting discussed, but this possibility has been commonly seen now. So now, this is also possible that you have this now and this is actually advantageous in certain lagging power factor situations from the point of your switching loss as we will come to later now.

Let me first you know clear up all the possibilities now. So, this is a case where it is clamped for something like twelve degrees here and let us say 48 degrees here. So, that is one possibility.

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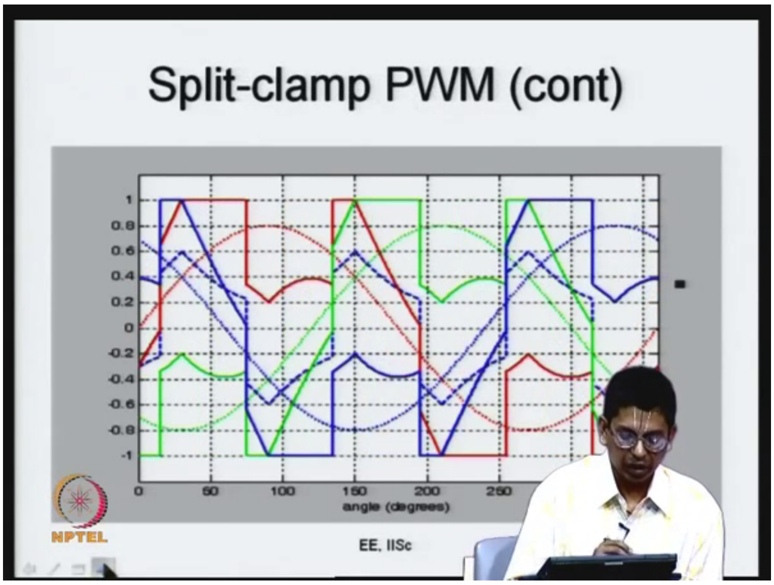

Now, I am showing another possibility here where it is clamped for something like 45 degrees here maybe and it is clamped only for 15 degrees here this is the R phase signal law. So, the 60 degree duration is clamped into 2 intervals and one interval falling in the first quarter cycle and other internal falling in the second quarter cycle of every half cycle of every phase now. So, you call it split clamp PWM.

How do you generate this how do you generate this for continual clamp you take one particular sine wave you are seeing the difference between this sine wave and V peak and that is what is added as the common mode component in the case of split clamp what you do is between 30 and 60 degree you are very your clamping R phase; for example, the common mode signal is really the difference between VP and m R and in the next thing what is getting clamped it is the y phase. So, the common mode signal is nothing, but the difference between minus VP and this signal and similarly here the blue phase you know this other phase is getting clamped.

So, here it is this and minus VP the difference between the 2 is the common mode signal and once again you go back to R phase. So, between 30 to 60 and 120 to 150 you use R phase signal. Now your common mode is VP minus m R and then this is done symmetrically for the other phase and on the other side the negative side also you get it that. So, this is how you get a 30 degree clamp and the generalization of this is you do not have to clamp from 30 to 60 and 120 to 150 you can clamp it from 30 to some 30 plus gamma and some 150 minus gamma to 150 your gamma can be anything between 0-130 degrees. So, this is a case where gammas some twelve degrees. So, this is clamped from 30 to 42 degrees and here it is clamped from this is 150; 150 minus gamma is something 102 degrees some 102 degrees to 150 degrees you have a clamp here now.

The other example that I am illustrating here is here gamma is something like 45 degrees. So, from 30 you are clamping till 75 degree here and what you do here this is for remaining 15 degrees up to 150; 135 to 150 now. So, the split clamp PWM has been found to be more advantageous than continually clamp PWM in terms of harmonic distortion which we will see in later lectures when you go into analysis of current ripple.

. So, this continuous clamp any of these continual clamp PWM methods you take and you take any of the split clamping PWM method you will find that is split clamp PWM method results in a lower harmonic discussion than the continual clamp that is one advantage of that.

the next advantage is you know really in terms of the switching losses continual clamp is suited for we I am just stating it; now I cannot prove it now I will prove it when we do the real analysis you know when we when really work out the switching losses and connection losses in the inverter and same that this continual clamp is advantageous when the power factor is high I will illustrate it very easily.

So, now let me take the 60 degree clamp PWM method. So, when the power factor is high that is when the power factor is unity. So, this is your sine this is the fundamental voltage this sine represents the fundament voltage power factor is unity again your fundamental current will be like this and the fundament the current will have its peak close to the voltage peak now. So, whenever the R phase current is going through 0 the phases is not switching and switching energy last is proportional to the current it is being switching. So, the phase is keeping quiet it is not switching when the current is going high and therefore, there is a substantial reduction there now.

On the other hand if it is not unity power factor load; let us say if it is a lagging power factor load if it is a lagging power factor load then this kind of a continual clamp is helpful now. So, these are many examples and if it is a leading power factor load then you can adjust this. So, this position of 60 degree has been adjustable that is sometimes called generalized discontinuous clamping or generalized bus-clamping PWM method and more advanced versions have also been derived from this now.

This is split clamping a particular cases split clamping where your clamping in for 30 30 degree duration, this is a more general case where you are clamping it for gamma and another 60 minutes gamma; gamma in one quarter cycle starting from 30 degree and 60 minutes gamma in the other quarter cycle ending with 150 degrees this is your split clamp PWM now.

And the split clamp turns out to be advantageous when you are talking of low power factors the inverter operates at a very high power factor for example, when your active front end converter etcetera some applications you do it is a UPF rectifier. So, something like a 60 degree clamp could be better there, whereas if it is like a stat com where reactive current is being given 30 degree clamp is possibly a good option there for low power factors when the power factor angle can be 80 degrees or so, such kind of clamp PWM methods are phone to be better as we will also see in this particular course now.

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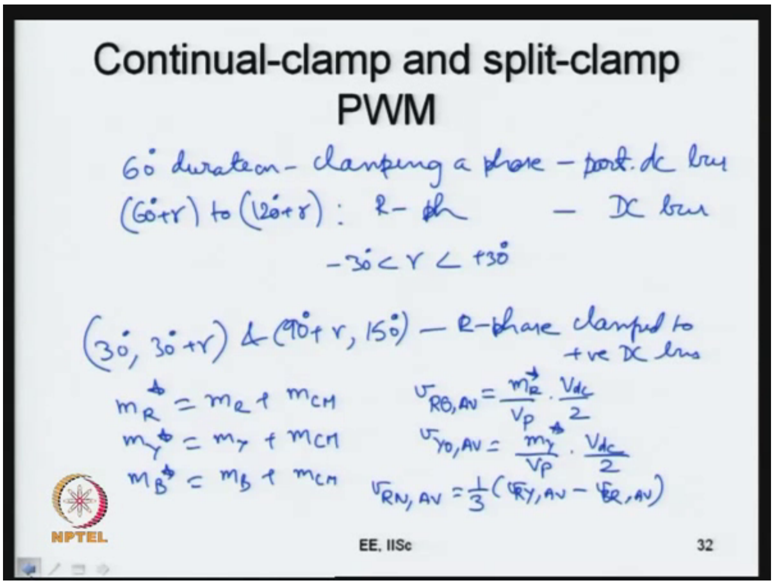

So, let us say a few more words on continual clamp and spring clamp now in both the cases what you are doing is you are clamping a phase for 60 degree duration. So, 60 degrees duration what is being done clamping; clamping a phase where to a particular DC bus to a particular DC bus.

Now for example, R phase may be to DC bus us what is the duration the duration can be some 60 plus gamma to 120 plus gamma this is the duration and gamma can be anywhere between minus 30 degree to plus 30 degree minus 30 degree less than gamma less than plus 30 degree. So, if it is minus 30 degree the clamping is between 30 to 90 if it is plus 30 degree the clamping is between 90 to 150 if gamma is 0; it is between 60 to 120 gamma can take any value in this range down and this is you call it as a continual clamping because the for its clamp the continuously for a 60 degree duration now.

Then on the other hand, if you have split clamping what you are doing is the 60 degree duration broken into 2 parts; say some 30 degree it come up 30 plus gamma; there is one possibility and 150 minus gamma to gamma is it right or is there is there a mistake here that is here it is for a duration of gamma here it is; I am sorry this duration ends with 150 degree and this is for a 60 minus gamma 150 minus of 60 minus gamma is 160 is actually 90 plus gamma. So, this is 90 plus gamma. So, this is the duration for which it is clamped. So, for this R phase is clamped R phase clamped to positive DC bus.

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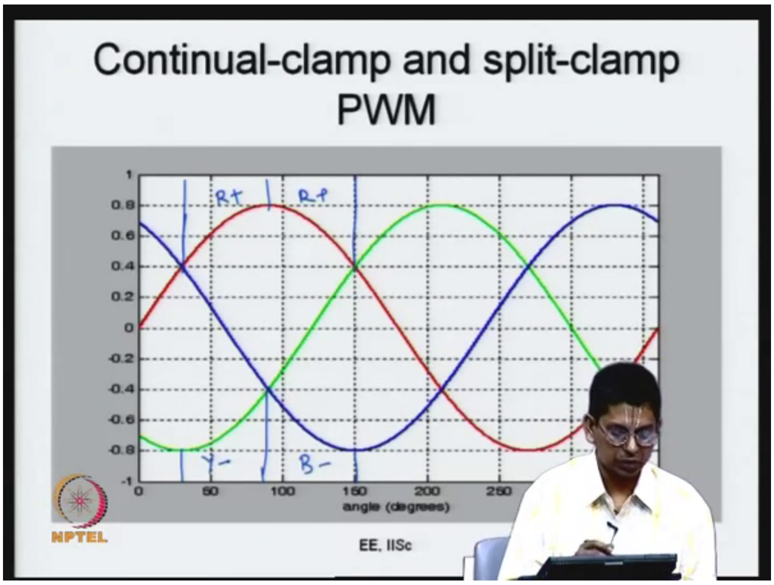

Let us look at the three-phase if you look at three-phase sinusoidal waveform somewhere that we make things clearer we have an option R phase for example, you can clamp it between here and here you can clamp to the positive DC bus. Now if you take this interval R can be clamped to the positive DC bus here also R can be clamped to the positive DC bus you take the next 60 degree interval y phase can be clamped to the negative DC bus you take the next 60 degree interval B phase can be clamped with negative DC bus now.

So, you have the situation where the most positive can be clamped to the positive bus and the most negative can be clamped to the negative bus. So, if you take this 30 to 90 degree duration R can be clamped to the positive bus or y can be clamped to the negative bus or 90 to 150 if you take R to the positive bus is possible or B to the negative bus is possible now. So, there is an option now for example, if you between this 90 to 150 whether you want to clamp R phase to the positive bus or B phase to the negative bus is a; it is an option now this option is what results doing this.

Now, in the case of continual clamp what are you doing you are clamping for some 60 degree durations here in the middle of this you are choosing a 60 degree duration to be somewhere in the middle somewhere in the middle and in the remaining part you are letting this y phase to be clamped to negative and you are I am sorry and you are letting the B phase to be clamped negative now.

In the case of split phase; what you are doing is there is some interval here at the start you are clamping it to be artifice to the posture again some interval to the end you are clamping it to that positive and in between what you are doing is in this region you are clamping y phase to the negative bus here you are clamping I am sorry; B phase to that negative bus. So, this is what is really being done there are 2 options clamping one to the positive another to the negative you are exercising these 2 options and so, you have this in this situation now. So, this is about our continual and split clamp PWM method now.

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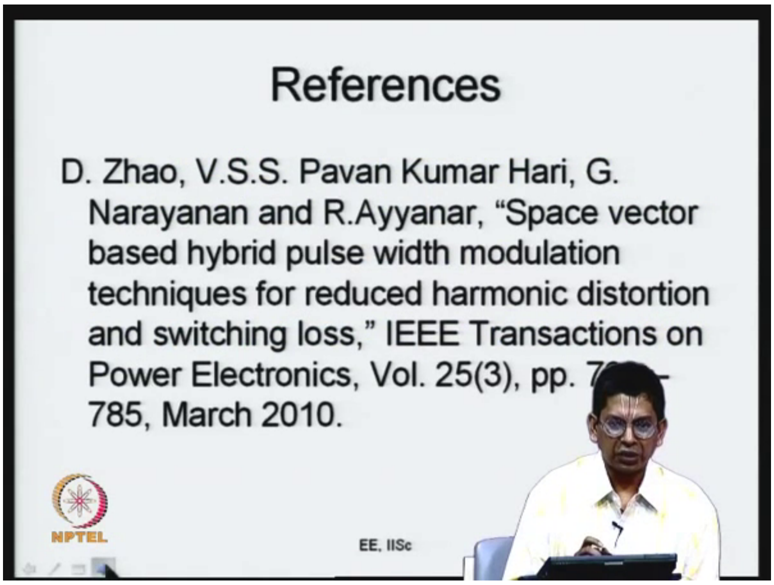

There are various examples you can look at more of this in one of the references that I can possibly give you there are some recent papers and one of them this particular paper by Zhao Pavan Kumar and Narayanan Ayyanar space vector based hybrid pulse width modulation techniques for reduce harmonic distortion and switching loss this paper essentially talks of certain advanced bus-clamping PWM methods which have which we have not covered till now which will cover at a later date, but in the run up to that the paper also discusses the bus-clamping PWM methods and where discuss is this continual clamping and split clamping methods now.

This clamping methods are very very widely known particularly what we discussed a 60 degree clamp is probably most universally known and 30 degree clamp is also known equally well has been widely used there, but the only thing is that 60 degree clamp can be generalized to continual clamp which is also being done again 30 degree clamp to be generalized to split clamping which is also possible you can see this continual clamping and split clamping much more easily when we deal with the problem of bus-clamping PWM from the space vector domain.

In the next few lectures; what we will do is we will move over to the space vector domain and we will start generating PWM start looking at PWM generation from the space vector point of view that point it will be very clear for you as to how to come up you know I mean these 2 possibilities have continual clamp and split clamp will be much easier to see now.

So, let me just can you finish up a few more things when I write this now. So, let us be very clear as to what we are doing in all these cases as I said we are adding a common mode component we are adding a common m R star is equal to m R plus m c M where m R is the original sine wave V m sin omega t. Similarly you are adding that to. So, m y star if you take is also equal to m y plus m c M and so on and you also have m B star is equal to m B plus m c M.

So, what you really have is now if you look at the average pole voltage that is pole meaning the midpoint of this. So, VRO measured with respect to the midpoint and its average value average meaning this VRO is averaged over a half carrier cycle if you do that what you are going to get here is this is going to be m R star upon VP times VDC by 2 this is what you will get now. So, what will be a VYO average VYO average will be similarly m y star by VP times VDC by 2. So, VYO average is equal to m y star times m y star divided by VP times V DC by 2 the same way you have VBO average also which I am not writing.

Now if I want to get VRN average this n being the load neutral also R phase voltage now measured with respect to the load neutral the load neutral is not electrically connected everywhere. So, if anywhere; so an average I will get it as VRO average minus VYO average of VRO average minus VYO average. So, this is my V R I am sorry this is VRY average minus V B R average that is you subtract these 2 VRO average and VYO average you subtract VRO average and VYO you will get VRY average similarly if you subtract VBO average and VRO average you will get V B R average now if you take VRY average minus V B R average you take one third of that you are going to result in VRN average now.

So, when you do VRY average itself now let me just clear up this part to discuss that I am sorry; now let us say right. So, I will have my VRY average and V y B average let me write down the expression for VRY average here what is VRY average VRY average is going to be VRO average minus VYO average.

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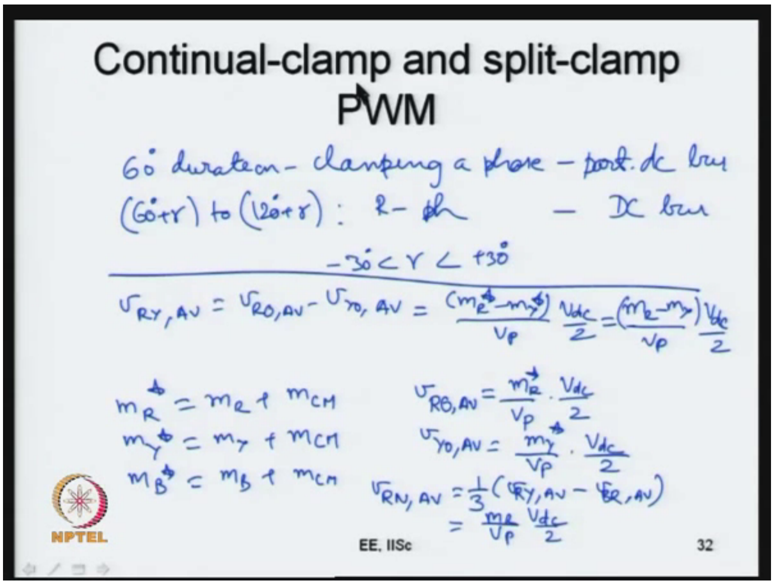

So, VRO average VYO average is what I have the same thing m R star minus m y star this is simply equal to m R star minus m y star divided by VP times VDC by two. So, m R star minus m y star is what m R star as m R plus m c M; m R star m R plus m c M m y star is m y plus m c M. So, m c M gets cancelled here what happens is simply m R minus m y. So, this is just m R my times by VP times VDC by let me just write that if you need that too sorry. So, this is m R minus m y by VP times VDC by 2. So, the line to line voltage does not have a common mode component, but you have the advantage that m R m R can go greater than one it can go all the way up I mean the peak value its m R speak value or m y speak value can go all the way up to 2 by root 3. So, that is one significant advantage of doing this bus-clamping the other advantage.

So, you see that that is not the whatever common mode is added here the common mode is there in the average pole voltages it is there in the modulating signals it is there in the average pole voltage, but this is the average line voltage R y is the line cline. So, this line cline voltage is averaged over half carrier cycle is VRY average that is VRY average minus VYO average. So, if this has a common mode component that has a common mode they get cancelled out that is what is there an m R star and m y star they get cancelled out. So, you get m R minus m y times VDC by 2.

So, the average line cline voltage does not have any common mode component and if you if you consider the load to be a three-phase star connected load as R y B with a load neutral n and the load neutral n is not connected anywhere and the load is balanced then you can write this VRN average in average in terms of VRY average and V B R average because your VRN is actually equal to VRY minus V B R one third of that.

So, VRN average is one third of VRY average minus V B R average if you do this you will go back to what is your VRO average. Now if I write this really down I what I would get here is this would turn out to be simply m R by VP times VDC by 2 goes back to the original equation m R by VP dens VDC by 2 just same as VRO average without the common mode component added there without the common mode component at this; now your m R can go much greater than one that is what accounts for the this

So, all these busts clamping methods can give you I mean a very good DC bus utilization they can also save the switching losses, but that depends on the power factor you should know to choose the correct PWM method for the correct power factor. Then it can also result in substantial saving in switching loss and among the methods there is continual clamp on this split clamp or 2 broad categories now and split clamp is a little better in terms of the continual clamp in terms of harmonic distortion.

So, these are the remarks that I would like to make. And I would you know I hope that you enjoyed this lecture and I look forward to your continued interest in the subsequent lectures when we will discuss further PWM methods.

Thank you very much.