Pulsewidth Modulation for Power Electronic Converters

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Lecture - 16
Harmonic injection pulsewidth modulation

Welcome back to this lecture series on Pulsewidth Modulation for Power Electronic Converters. We were looking at various power electronic converters and then we were looking at the you know see essentials of pulse width modulation such as Fourier analysis and all, we will looking at low frequency PWM, we looking at selective harmonic elimination and certain optimized to offline PWM.

Now we are talking of more of real time or online PWM where the PWM generation is done in real time and at high switching frequency. Last class we started off with sinusoidal modulation. So, today we would try to do a little more on modulation. Now it is going to be a harmonic injection pulse width modulation now.

So, it is a little interesting I have often been asked this question; professor you eliminate harmonics earlier in that selective harmonic elimination classes, but now when you come to this harmonic injection you seem to be injecting harmonics. Well, to put it jocularly I would call these harmonics as friendly harmonics; that is these harmonics are harmonics, but they really do not matter I mean they will not affect the performance of your motor drive. So, that is how it is going to be.

So, let us see what kind of harmonic injection is being done now. It is actually going to be some kind of second harmonic injection for the single phase inverters and it could be three-phase symmetry with the more useful cases third harmonic injection in the case of three-phase inverters.

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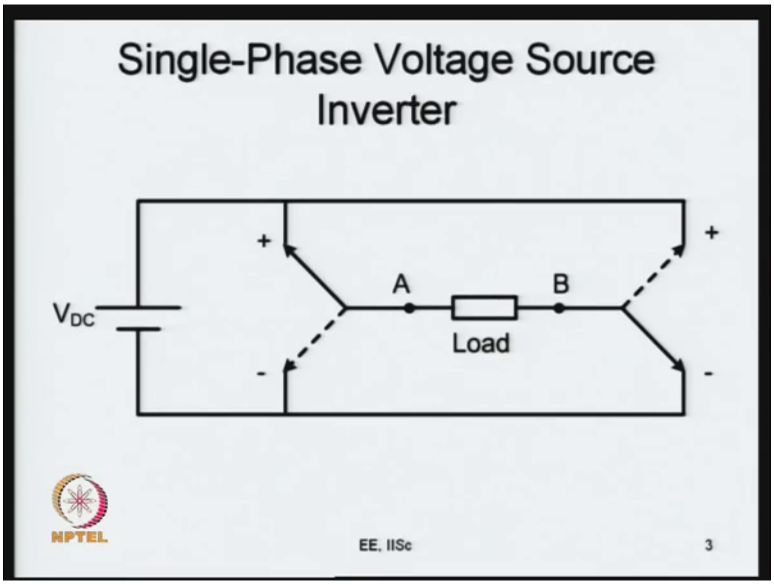

So, let us just get started. So, once again if you go through the basics this is a voltage source inverter and in the case of voltage source inverter what you have it is essentially there is a load this is a single phase voltage source inverter. So, there is a load and the load has 2 terminals and the load is presumed to be inductive. And therefore, every terminal is connected to a pole and there is a single pole double throw switch once again you have a single pole double throw switch there are 2 single pole double throw switches.

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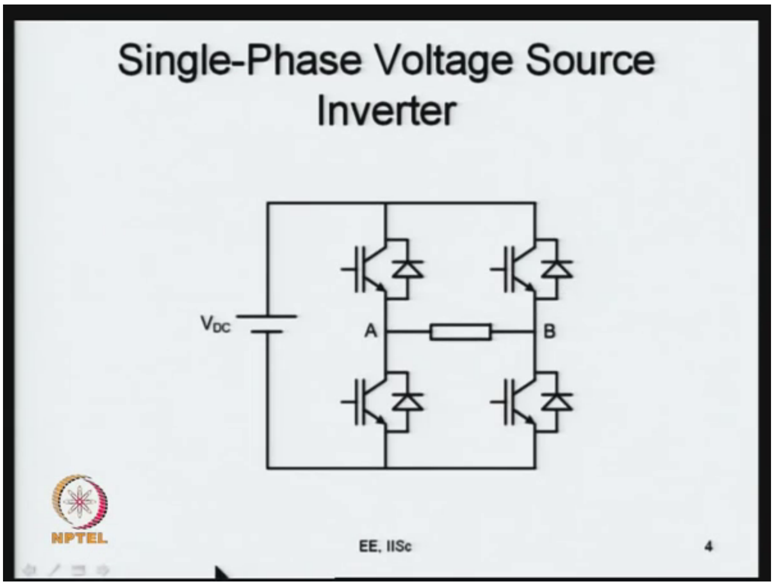

As we know and these single pole double throw switches are realized using these kinds of transistors. So, what do we do we switch these transistors on and off in a complementary fashion if the top is on the bottom is off and vice versa the same way, we can do this and both these legs can actually be controlled independently, all right.

So, in the case of the so called bipolar PWM what we do is we keep these 2 on and the other diagonally opposite switches off that would apply VDC with particular polarity and in the other way what you do is you apply the other diagonally opposite switches are kept on the other 2 are off that applies minus VDC. So, this plus VDC and minus VDC can be applied across the load for varying durations that is bipolar PWM because between this VAB output in the positive cycle as well as in the negative of cycle of the fundamental voltage you see positive pulses as well as negative pulses that is what we saw in the last class. So, that is the bipolar PWM and we would more use the more popular uni-polar PWM.

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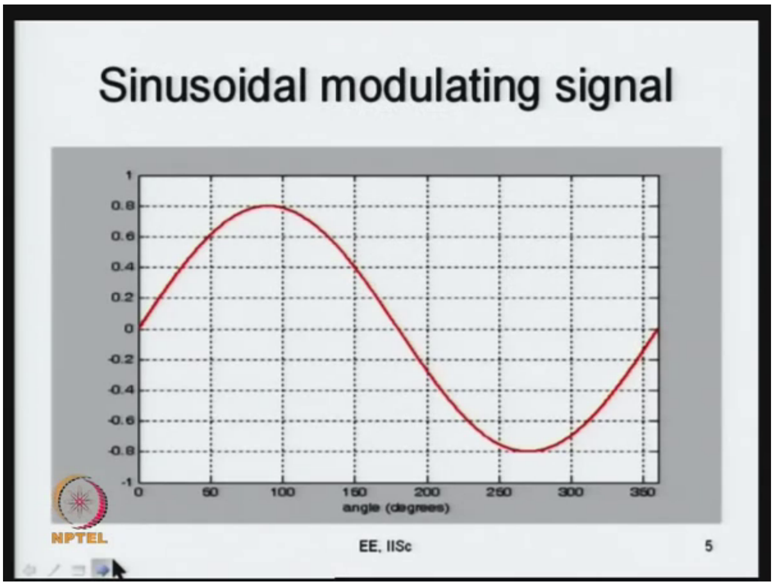

So, if you go to that unipolar PWM; now first let us just look at one leg one leg and one sine wave corresponding to A leg now. So, why do we use a sine wave the idea is the average pole voltage that is you had the pole before you had the pole the voltage at this pole we wanted to be modulated in a sinusoidal fashion with respect to the DC bus midpoint that DC bus midpoint is not indicated here you can regard this VDC as VDC by

2 and another VDC by 2 and the midpoint can be regarded as O. So, that is the DC bus neutral.

So, if you modulate this average voltage at a; in a sinusoidal fashion and also modulate the average voltage at B in a sinusoidal fashion the difference between the 2 will certainly be a sinusoid. So, that is an idea. So, now, you use a sinusoidal signal. So, use a sinusoidal signal this is for one of the phase now.

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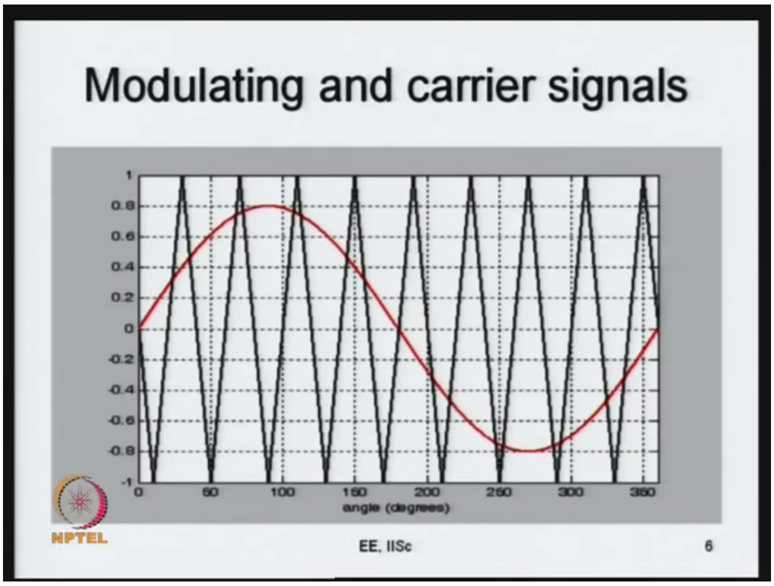

So, what you do with that you actually compare a triangular carrier, this is a high frequency triangle and carrier as I said you have indicated when I have considered a frequency of nine times fundamentally it could be bigger much bigger than this at a nominal power levels you know like few kilowatts, etcetera, it can be size if it inverters this carrier frequency can be as high as 15 kilo hertz, 20 kilo hertz in case of mass fit inverters, it could still be higher depending on what is the rating that we are talking off very high power levels this could be lower that is for example, where you use IGCTs or GTOs this carrier frequency could only be a few hundred hertz. So, we have a model and we regard this for all purposes of this study we regard this carrier signal as a high frequency signal whose frequency is much higher than that of the modulating signal.

So, that in one carrier cycle you can regard the modulating signal to be almost flat. So, there is any changes that you have it that can be ignored top.

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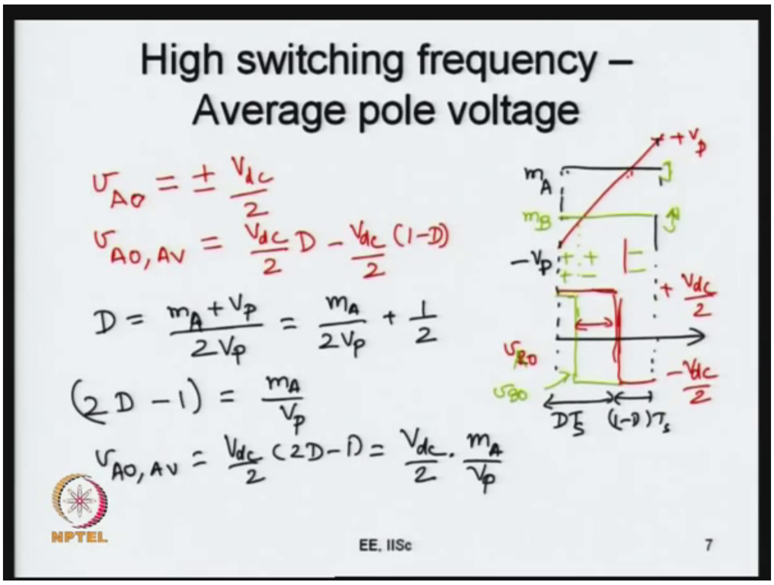

Now, you have the high frequency in the; you know when you are considering high switching frequency you can always look at the average pole voltage concept. So, what is this average pole voltage concept. Now you have V AO and this V AO is equal to either Vdc by 2 or minus Vdc by 2 where O is the midpoint of the DC bus when a top device is on this voltage is equal to plus Vdc by 2 when in a bottom device is on only one of the 2 devices can be on you know. So, in the bottom is on it is going to be minus Vdc by 2. So, what do you do is in a small interval of time which is equal to the half carrier cycle. So, what you do is you sometimes apply plus Vdc by 2 and you apply Vdc by 2 for the remaining duration.

So, you have certain average voltage, I put it as V AO this is the average value average value of what average value of V AO over what interval over a half carrier cycle one half a cycle of the carrier. So, for a half cycle of the carrier what happens you apply Vdc by 2 for how long for whatever is the duty ratio D times Ts, then you apply minus Vdc by 2 for the remaining duration which is 1 minus D times Ts and you average, it you will average pole voltage will be equal to Vdc by 2 into D minus Vdc by 2 multiplied by 1 minus T this is what is going to be your average pole voltage.

So, this is the average pole voltage this is the relationship between the average pole voltage what do we mean by the average pole voltage pole stands for the pole of the single pole double throw switch every leg is a single pole double throw switch. So, the pole refers to the midpoint or one of the load terminals and we are talking of this pole voltage that pole voltage is measured with respect to O that O is the DC bus midpoint and we are talking off its value averaged over a half a carrier cycle.

So, what you are trying to do is sometimes you are applying Vdc by 2. And sometime you are applying minus Vdc by 2 how do you exactly do that for example, let us say you consider a half carrier cycle this is one half carrier cycle, I have drawn the carrier wave form here and now this is your modulating signal this is your modulating signal. Now let me call this as plus VP and this as minus VP these are the positive or the negative peaks of the carrier, but is not clearly visible this is minus VP now.

So, what do we do when we are switching whenever the modulating signal is greater than the carrier. Now I regarded the modulating signal as a DC why because we are looking at a very short interval of time let us much shorter compared to the fundamental cycle and therefore, you can ignored whatever variation that you have in the sinusoid or you can take it is a sampled value of sine. So, it is a flat line now here. So, what do you do you compare the sample the sine wave and this carrier. So, now, whenever the sine wave is greater than the carrier the top device is on so; that means, during this interval you have plus Vdc by 2 is applied you have plus Vdc by 2 applied and during the rest of the interval it is minus Vdc by 2 is getting applied now.

So, let me change the color. So, this is right. So, let us redo that with plus VP and minus VP clearly this is plus VP. And you have minus VP and then I have the carrier signal I mean I have the modulating signal this modulating signal I will draw like this and this value let us call it as mA; this is the modulating signal corresponding to a phase now. So, let me draw dotted lines here this is the starting of the interval this is the ending of the interval. Now what is the voltage that you have here during this up to this instant up to this instant you have VRO is positive and here VRO is negative this is VRO and VRO here is plus Vdc by 2 here, it is minus Vdc by 2 and where is the 0 line somewhere like this; this is the time axis.

So, what you are applying is as I said this VRO plus Vdc by 2 is applied for certain duration of time and that duration of time we call this as the duty ratio times whatever Ts Ts is the half carrier cycle and this remaining time is 1 minus D times Ts; this is a more detailed explanation of why I have written this equation this way. So, this is how you do a comparison therefore, you have Vdc by 2 times T and minus Vdc by 2 times 1 minus D this is your average pole voltage now.

So, I have expressed this average pole voltage in terms of duty ratio let me try and express it in terms of mA how do we do it in terms of mA first let us say this is the duty ratio D how is the duty ratio D related in terms of mA for a duration of time equivalent to mA minus of minus VP the top device is on for the remaining duration equivalent to VP minus mA the bottom device is on. So, I can say mA minus of minus VP that makes it mA plus VP divided by 2 VP this is the duty ratio this is the time for which the top devices on now.

Let us just simplify this expression or I mean just split it up this becomes plus half. So, this is how duty ratio is related to the modulating signal value and VP they that is the peak of the carrier if we take peak of the carrier to be one you can simply call it mA by 2 plus half now. So, let me write it the other way if I take it this 2 D I am taking this 2 in the denominator to the other side minus 1 is going to be equal to mA upon VP is it right goes off to the other side. So, it is 2 D.

So, what you have is mA by VP plus one. So, 2 D minus 1 is equal to mA by VP. So, what is this expression exactly V AO average V AO average there is Vdc by 2 times D of Vdc by 2 and there is minus d. So, this is exactly what you have here is let me go back V AO average itself is Vdc by 2 times 2 D minus 1 from the previous equation and that is nothing, but Vdc by 2 times 2 D minus 1 is equal to mA by VP.

So, we have the average pole voltage related in terms of DC bus voltage and duty ratio first and duty ratio is related in terms of the modulating signal and the peak of the carrier and once again you know the this is the other these 2 are related like that this is here the duty ratio is expressed in terms of mA; mA in terms of duty ratio. So, what you get this is V AO average is expressed in terms of mA and VP now. So, you can say your duty ratio at the average pole voltage is Vdc by 2 times 2 D minus 1 or it is Vdc by 2 times mA upon VP in terms of the modulating signal now.

Now, in this modulating signal is sinusoidal m is sinusoidal for us here. So, if mA is sinusoidal you are going to get a sinusoidal average pole voltage that is the idea this is what you do now this is the idea of using a sine wave also the average pole voltage varies in a sinusoidal fashion because this mA that you have here is the sinusoidal signal.

So, we can call it some Vm sine omega T or so and you go about doing there now. So, this is your average pole voltage now why do you do this now if you have va as average pole voltage now I may rewrite it here. So, excuse me.

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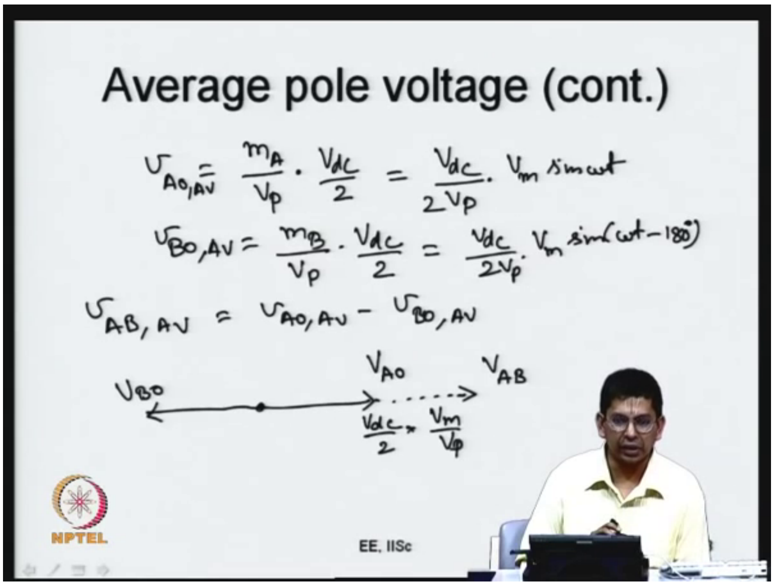

So, I have V AO is what mA by VP times Vdc by 2 my mA can go as is VP not beyond that that would be called over modulation and you know it will just get clipped to VP in any case. So, the maximum voltage that this is the average pole voltage the maximum value of the average pole voltage can only be up to plus Vdc by 2 the minimum voltage can be minus Vdc by two. So, the maximum amplitude it can take as Vdc by 2 . So, V AO average can be Vdc by 2 sine omega T if your wish now what is V BO average V BO average similarly instead of the A leg for the B like we have another sine wave and that divided by VP times Vdc by 2 and what is your VAB average that is applied on the load what is applied on VAB average is actually V AO average minus V BO average this is what you apply is it right.

So, this is a sinusoid that is a sinusoid. So, here what do we have Vdc upon VP to VP; let us call it some Vm sine omega T and what we have here Vdc upon 2 VP. So, the mB is also sinusoidal signal of the same Vm and its also sinusoidal signal same frequency, but it is phase shifted by 180 degree in the case of a three-phase inverter this will be phase shifted by 90 degrees now. So, V AO average will be a sinusoidal waveform. So, if V AO average could be a sinusoid like this that can be regarded as a phasor and what would be the amplitude of this phasor the maximum value it can take as Vdc by 2 and this Vdc by 2 is multiplied by Vm upon VP this Vm upon VP is usually called modulation index by many people because it gives you how much of AC voltage you are really trying to produce and then where is your V BO same this is except that it is in the opposite direction I am writing it as capital V AO and I am writing this as capital V BO by this I mean that pao is essentially just only a sinusoidal quantity we can do a phasor sum.

So, if you do a phasor difference; what happens essentially this is here v is sum of the 2 this is your VAB right. So, you get this; that is how you subtract us. Now if this were a three-phase situation what you will have is we will have a VRO average pole voltage when we will have for Y phase there is one average pole voltage for B phase there will be one average pole voltage and those average pole voltages will be phase shifted by 120 degrees now . So, this is what we have in terms of sinusoidal modulation now in case of single phase inverter in case of unipolar PWM we are going to use just an mA and mB both are sinusoidal signals at the fundamental modulating frequency both are the same amplitudes, but they are the sine inverse of one another their phase shifted by 180 degrees now.

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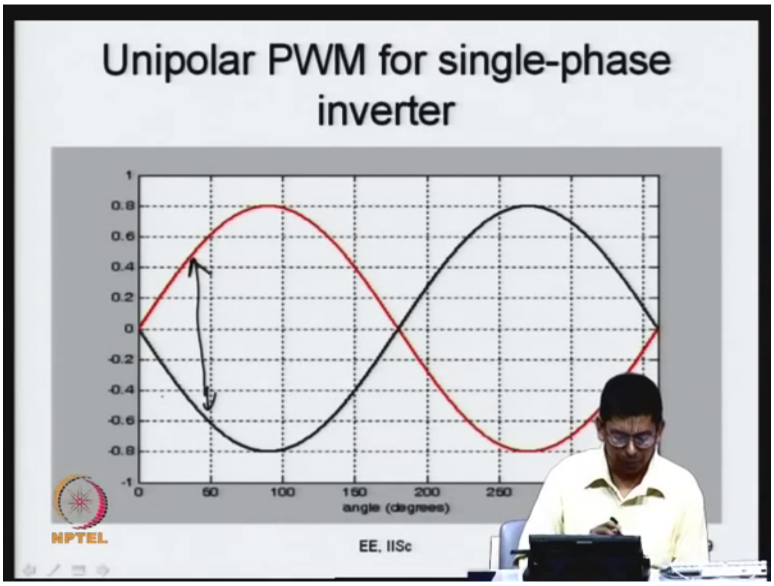

So, there are certain possibilities different waveforms are possible this is what we are trying to do what we are trying to see is this is what you are trying to get what is that the top waveform represents V AO ave; this is the mA the modulating signal for leg a black waveform represents the modulating signal for phase B or it is the modulating signal for phase B the red signal represents the average pole voltage of A leg the black signal represents the average pole voltage of B leg what does the difference between the 2 represent what is the difference between the 2 represent the difference between the 2 represents the average load voltage it is the difference between the 2.

So, essentially what you can say is let us say the a phase voltage is slightly shifted up by a small amount, let us say you know on this scale let me say it is about 0.01 and the B phase is also shifted slightly above by the same x to the same extent say the same 0.01. So, what will happen the a phase signal will not look like sinusoid it may be phase shifted or it could be some other signal also again B phase signal also will not look sinusoidal I mean maybe are its level shifted sinusoid or whatever, but the difference between the A leg and the B leg is remains unaffected the average output applied on the load is unaffected. So, can be shifted slightly upon B also can be lifted slightly up that is what is called as common mode now.

So, if you look at it in terms of the inverter what happens; it is closely related to the redundancy of the inverter.

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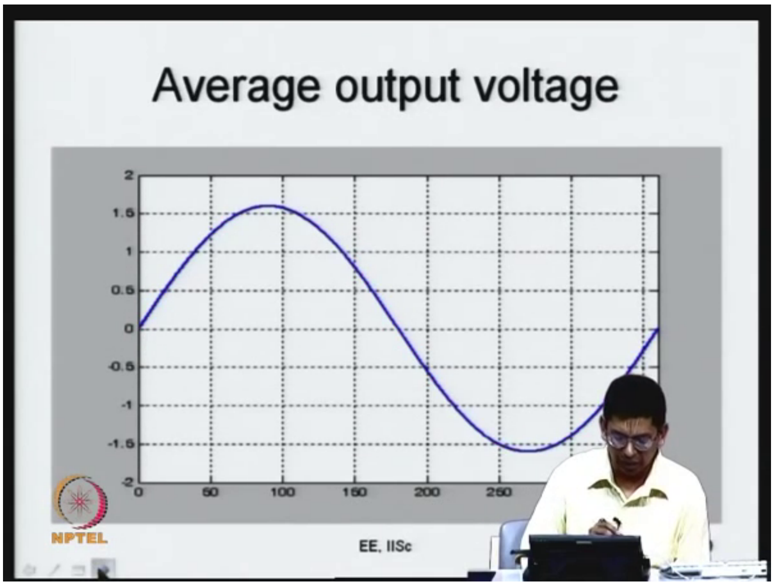

So, here even if you do this, this is the average output voltage what is this average output voltage this average output voltage is the average pole voltage of A leg minus the average pole voltage of B leg. So, if they are simply sinusoids are shown here and with certain small amount of common mode added to both of them it would be the same right.

Now, let us say what is that common mode why does it come up what you will look at a three-phase inverter now in a three-phase inverter I mean sorry; now first a single phase inverter we are still looking at a single phase inverter you have a load output.

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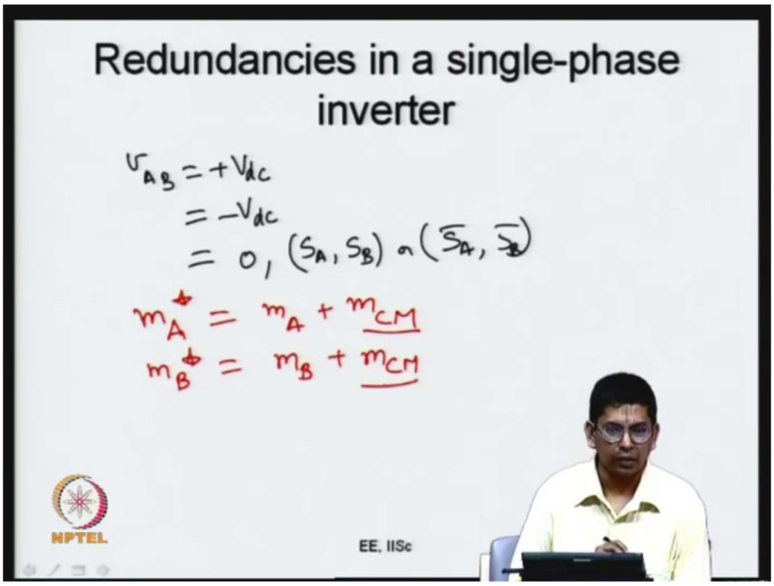

Let us call is VAB; VAB can be equal to plus VDC and it can also be equal to minus VDC it can also be equal to 0 when is equal to plus VDC when the top device of one A leg and the bottom device of B leg are on when it is minus VDC the opposite situation when is 0, it a there are 2 things both the top are on both the bottom are on that is both SA and SB both of them can be high or it can be SA bar or SB bar meaning both the signals can be low in all these cases you have this situation. So, if both the top is on and both the bottom is on in both the cases you will have this situation.

Now there is a redundancy this is what we call as a redundancy the output voltage is the same, but it can be applied in 2 different ways. There are 2 different inverter states which apply the same output voltage now this is what you would call as a redundancy it does not matter to the load the load just is a short, but it matters to the inverter because which device conducts on which device does not conduct depend upon which of the 2 states that you have used now. So, this redundancy is closely related to what we are trying to do let us see what we are doing to little further.

Now we looked at the sine waveform we looked at this earlier on the same thing let us say I its I do an mB also there is B phase also correct let me take another color and I let me call this as mB. So, earlier we were seeing only one signal. Now we are take same 2 different signals that is I am showing the second leg signal also if I am doing my mB leg this what would be the B phase voltage I am sorry this is not VRO this is V AO how would V BO look like VB would look like something like this V BO would look like something like this it will be a plus VDC by 2 for a short duration and then it is minus Vdc. So, this green color is V BO.

Now, what are the inverter states applied if I take the first interval when both mA and mB are higher than the carrier signal. So, I would write it as plus plus meaning in both the legs the top devices are on then in the second case if I see in the second interval what happens the B leg switches, but the A leg remains unchanged it is like this if I look at the third interval what happens both of them are negative.

So, this is the same situation would prevail if I shift mA and mB up by a small extent or both mA and mB down by certain small extent now as long as the extent of shifting up or down is very small now if I shift up or down what happens let me indicate that here I can shift this up or down I can shift mA also up or down by a small extent that is what is called as common mode rejection now if I shift up or down both to the same extent what happens you have this distance between these 2 the distance between these 2 is unchanged.

So, that is really the pulse width for which the VDC is applied this is the duration for which the actual voltage pulse is applied across the load. And in the first interval the load is shorted on the third interval is also loaded shorted if both mA and mB are moved a little upwards what happens is the time for which this plus and plus applied is a little longer and the time for exists minus and minus applied is a little shorter there are only changes in these 2 intervals these 2 intervals change, but the middle interval remains unchanged if interval plus plus increases the interval minus minus decreases; now that is because of the redundancy.

So, you can apply 0 voltage to the load either using either by switching all the both the top devices on or having both the bottom device is on. So, this is what you are doing. So, when you are adding common mode voltage the time for which you are using both the top devices and the time for which you are having both the bottom device is conducting it changes. So, that is why I said it is related to the redundancy the redundancy of this is what let us you to add such a common mode voltage. So, this is what we mean by redundancy. So, these 2 legs can change and you can go about doing now.

So, what you can do is you can consider adding certain common mode signal that is you have your mA this mA you can call it some mA star which is to mA plus certain mcM which is a common mode signal and then you can look at mB star which is equal to mB plus the same common mode signal as long as the common mode signal is small right how small is small the sum of these 2 mA plus mcM; the new mA star at any instant of time on the line cycle should not go more than plus VP the positive peak of the carrier are should not go below the negative peak of the carrier as long as you do that what is the purpose in doing that we will discuss it later they are may not be any purpose also, but I am trying to say theoretically it is possible for you to do this on account of the redundancy by adding this now.

The next thing is what should this common mode component B if it should be the same the common mode component could actually be a small amount of DC and if you see it can also be a small amount of AC because what is the difference between AC of what frequency of double the frequency double the frequency of the fundamental why. So, what are you getting mA and mB what is the relationship between mA and mB; what is the relationship between mA and mB; they are phase shifted by 180 degrees. So, if you add an even harmonic component there to mA and phase shifted by 180 degree the even harmonic component just going to remain the same and when you do a subtraction the even harmonic component will vanish.

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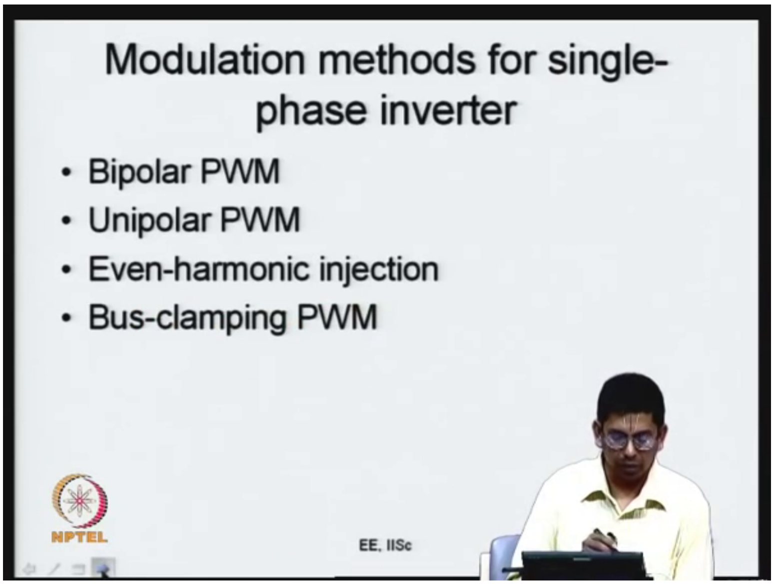

Let us look at closer examples you know in the next slide or so.

So, we first add the bipolar PWM which is the simplest way of switching only the 2 diagonally opposite switches or on at any point of time the control is very simple, but the harmonic destruction could be very high in this right unipolar PWM is reasonably good I mean that is probably what you could regard as standard technique if you want to choose one technique you know I think most probably you would go and do choose a unipolar PWM unless you have any reasons to shift to something else I would call it as a default option for somebody who might work with single phase inverters now there could be reasons why you want to choose something else you.

Now, on this unipolar PWM it uses 2 different sine waves on that it is possible to inject a even harmonic if you add an even harmonic what happens is that is a common mode component then you add a small even harmonic I am going to demonstrate it in the next slide and this also can lead to what is called as bus clamping. So, that I will talk about little later the kind of even harmonic components can be added could be such that it leads to bus clamping that is one of the legs not switching for certain amount of time, but continuing to remain clamp to either the positive bus or DC negative bus for some amount of time.

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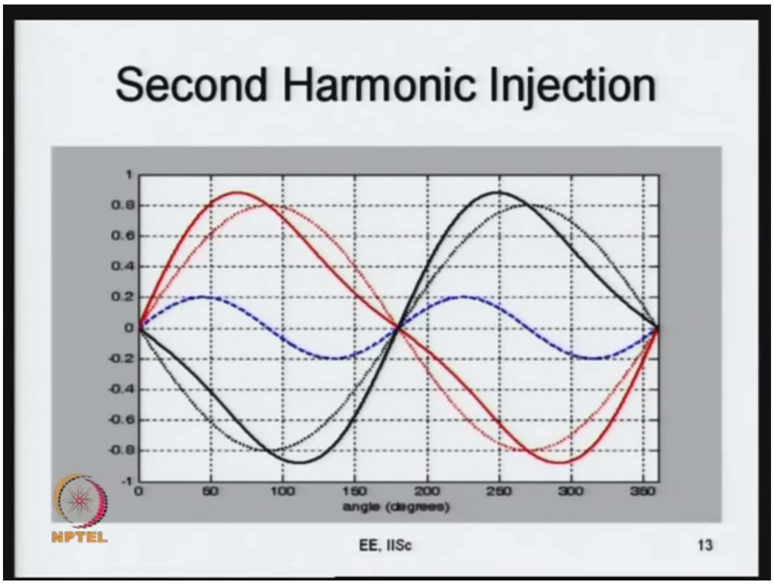

So, let us look at this even harmonic stuff.

Now the dotted lines that you have the red phase and then the dotted lines you have the black or the A and B leg original sinusoidal signals on top of it what I am trying to do this I am just trying to add this blue signal here shown and dashed lines what is that that is common mode and that is actually you can see that it is double frequency, it is an even harmonic it is a second harmonic to be very precise. Now I add the second harmonic as a common mode component to both my red phase and the black phase. So, what happens here; you see that the actual modulating signal is now different and actually modulating signal for the black phase is different.

Now would this affect the output no why because the red signal is the average pole voltage for a phase and this black signal is the average pole voltage for B phase and the difference between the 2 is unaffected V AO average is changed V BO average is changed, but the difference between V AO average and V BO is average is not changed that is going to remain the same as what we saw before that is the same kind of sinusoid that we had here same kind of sinusoid that we had here.

So, you have this is there a point in adding it; it could be a question just hold on there may not be a point, but a similar third harmonic injection is possible in the three-phase inverter and that is pretty much valuable. So, let us see what we can do about this now. So, all I can say is you can add a second harmonic like this of a small amplitude and you see that the red phase thing increases the black phase negative peak goes down further here again the black phase thing goes further. So, the peak values are going the modulating signal is no longer quarter wave symmetric earlier the sine wave is nicely symmetric about its peak about 90 degrees, now it is no longer. So all this happens, but it is, but the final output voltage will be unchanged now.

So, there is no point essentially a you can, but nevertheless you can add a small value such that this peak value at this peak value do not go beyond plus VPR minus VP now. So, now, it is possible to add fourth harmonic like this sixth harmonic eighth harmonic anything any even harmonic really like this now.

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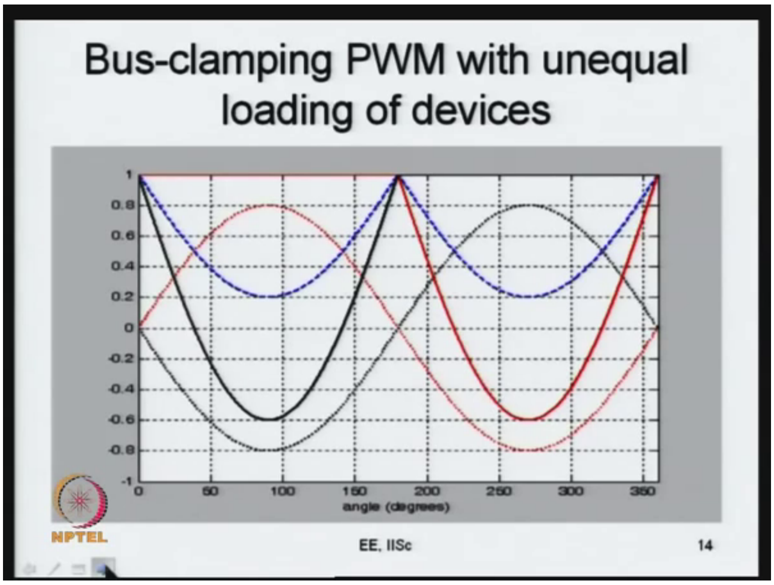

You can add that in such a fashion that you know any signal which is set double the frequency. Now this you see this blue signal what is this blue signal; what is the frequency of this blue signal twice the modulation frequency you see the red sinusoidal wave that if you call it as 50 hertz; this blue is at 100 hertz. Now you add this blue signal to both of this; however, I derived this blue signal in the first place I have subtracted 1 minus the red phase sign to get the blue signal here what I have done in the second half cycle I have subtracted this black this is I mean from minus 1 here. So, I am I have got the same kind of difference between these 2 here now.

So, now, what I am trying to do is this is I am adding this blue signal I am adding as common mode to both red and black. So, what happens the red signal goes and gets clamped here and the next time around what happens the black signal goes and gets clamped here what do I mean by clamped the modulating signal becomes equal to the carrier peak. Therefore, there are no intersections and the positive device of A leg is continuously on here on the you know top device of B leg is continuously on here. So, A leg does not switch at all here. So, it is low on switching losses again B leg does not switch at all here it is low on switching losses when switching frequencies are very high every time you turn on and turn off there is certain amount of energy lost when the switching frequency is high the switching loss is going to be high we will do some detailed calculations a little later some few lectures away, but now you can just see this now.

So, what it does is it saves certain amount of switching loss for you energy lost on account of switching A leg here you save certain amount of energy on account of nots by not switching the B phase like now. So, this is what is called as bus clamping because a phase remains clamped to the positive bus here and B phase gets clamped to the negative bus here. Now you call it as bus clamping pulsewidth modulation now. So, it can reduce that the switching loss, but I is it desirable there is something that we have to observe now you see that the top device is conducting here.

And in the second half both the top and the bottom devices could be conducting. So, you see that the top device is conducting for longer time than the bottom device in the a phase leg the same way in the B phase leg in this entire half cycle the top device is conducting whereas, in this half both top and bottom are conducting; so overall again in the B phase the top device is going to be conducting now.

So, this is a situation where one leg in every leg the top device is going to be heated up more there is going to be more loss in the top device than in the bottom device that is what I mean by unequal loading the heating of those devices the top and the bottom devices are going to be different and that is not very desirable because by and large you would choose devices which are equally my its they have a same rating. So, if you re going to heat up one and not use well or the other one that is not an optimal utilization of the devices that you do; so, this bus clamping is good in so far as it reduces switching loss, but this is not good enough because the losses in different devices are different.

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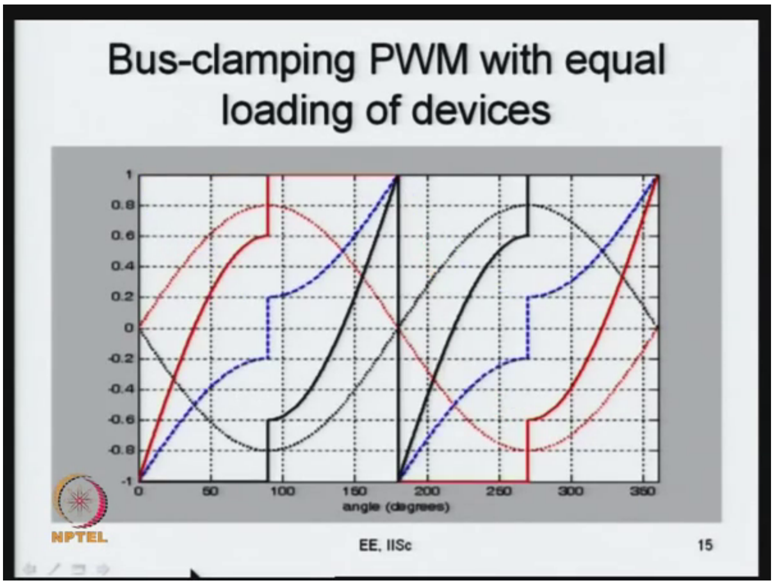

So, now what we are going to look at is we go to see whether we can make this losses equal that is what has been done here now how do you do that now.

Here I have just derived my common mode a little differently you see that this is common mode and you see this is how it is you can see it is periodic over 180 degrees you can saw it you can see its fundamental you know frequency is 2 times the actual fundamental modulation frequency; now how do I derive this I have subtracted 1 minus this I mean I am taking a phase and taking the difference between that and here some time here I am taking the B phase what I have done is I have take the difference between B phase and this other signal now. So, I go about doing that.

So, either a phase or B phase I choose and I subtract if the signal is going positive I; I subtract 1 minus that signal if the signal is negative I am subtract minus me mean minus that signal from minus 1 now. So, this is basically result of subtraction of you know from plus VP or minus VP a particular leg signal. So, this you get it like this and this you get it like this.

When this common mode is added to the 2 leg signals a signal changes as shown in the solid line here it is no longer sinusoid it goes down here; it is clamped it goes down like this now. So, what are you achieving now here in this 90 degrees duration a phase stop device conducts in this 90 degree duration it is the bottom device is on and the bottom device conducts. So, the switching loss is reduced a phase switching loss is reduced by

50 percent because 50 percent of the time a phase is not switching and the conduction losses are also uniformly distributed between the top and the bottom device.

Now, similarly you take the leg B which is shown in black ink now during the first 90 degrees it is the bottom device of leg B that is on during the last 90 degrees shown here the top device is on. So, there is no switching loss here there is no switching loss here also in B phase leg and the conduction of the 2 devices are more or less equal and you end up in equal loading of devices.

So, this is one way. So, what you are trying to do is you are adding some even harmonic injection this is not just second harmonic this is this is not a sinusoidal waveform this waveform is at a fundamental frequency of hundred hertz if the if the sign is taken as 50 hertz, the blue waveform is at 500 hertz. So, what are the frequency components of the blue waveform 100 hertz, 200 hertz, 300 hertz, 400 hertz, 500 hertz, etcetera. So, it has lots of all the even harmonic components here 2, 4, 6, 8, everything is there now, but it does not have DC in this as you can see in this case. Now that is a requirement you know otherwise it could end up in uneven loading of the top and bottom devices and also you see that these 2 waveforms are actually similar the red waveforms in the black waveform you see similarity between the 2.

So, you what you get is you know you have the equal loadings of the 2 legs and also for the top and bottom devices now. So, you are able to add this kind of blue common mode signal and you are able to reduce your switching energy because you are switching at very high frequency you may want to reduce that. So, this has the benefit of giving you a lower switching loss and also equal kind of devices here now. So, this is in one of the references which I will give at the end of this lecture which I also indicated in the previous lecture.

So, if the same thing you know this is slightly differently done that is the choice of phase which phase VP subtracted from etcetera is different now. So, here what I am trying to do is from one I am subtracting this to produce over the first interval and then I am using the next phase, I am subtracting in from minus 1 to produce the next one. So, I get my common mode signal like this. So, now, the common mode signal the blue signal is different, but you can see that it looks very similar it is just flipped around excuse me and. So, this is what you have; now here A is clamped here the top devices conducting continuously for 90 degrees when the bottom devices continuously conducting for 90 degrees now.

So, a phase does not conduct for does not switch for half the time. So, switching energy is saved I mean the loss on account of switching is saved and the conduction is also uniformly distributed between the top and bottom devices and also between the 2 legs. So, you even harmonic injection you have no advantage, but you can possibly have this advantage what you can do bus clamping that can resultant lower switching energy loss and also ensure that you know by enlarge there are several methods these methods are relatively I mean not. So, widely known that is you know bus clamping methods are known, but bus clamping methods for single phase inverters which would result in equal loading of devices are not. So, very widely known it is contained in one of the references that I am given there now.

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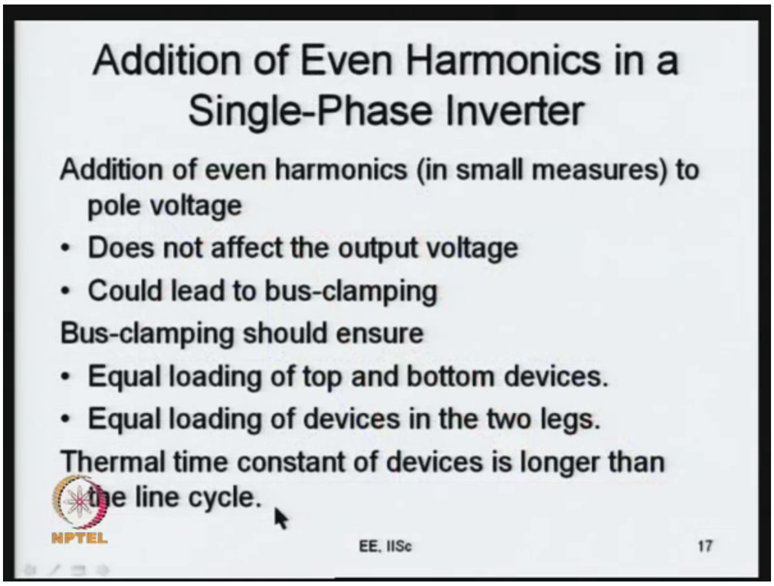

Some comments on the even harmonic; now it is possible to add even harmonic what do you do; you can add even harmonic there are 2 sine waves for A leg and B leg which are phase shift will be 180 you can add a small amount of even harmonic provided the peak values of the 2 waveforms do not go beyond plus VPR minus VP. So, that does not affect the output voltage as long as you add it in small machine, because the difference between the 2 modulating signal should still be the same and if you add it properly if you derive your common mode voltage properly, it is possible that you could ensure bus clamping and if you ensure bus clamping you can reduce switching loss necessary.

So, on bus clamping has to be done in such a fashion that it ensures equal loading of the top and bottom devices which is what we tried an ensured now and also equal loading of devices in the 2 legs. So, this is what we have done now there is one assumption here which I have given at the end here what is that assumption that I am giving here, the thermal time constant of devices is longer than the line cycle that is you what is your basic assumption you go forward here this is not conducting that is I mean one device is conducting and here another device is conducting now because it is conducting there certain amount of loss heat is being dissipated now and this I mean this heat is going to increase the temperature, but there is a delay between the junction temperature rise the junction temperature has some maximum safe maximum value when the device conducts or because of switching action the device dissipates energy when it here it conducts and therefore, it dissipates power and in this region the devices are switching and an account of both switching and conduction there is some power dissipated now.

This results in increase in the junction temperature, but there is a delay the moment there is power dissipation your junction temperature does not increase there is a delay and that is what is called as thermal time constant there are various time constants involved there. So, there are certain thermal time constant now. So, what we assume is one what is true in most practical cases in most practical cases this is a like 50 hertz like 20 millisecond cycle or maybe 60 hertz in some countries and you want to vary in the variable frequency use you may come down to 5 hertz or whatever now. So, if nominal frequency is 50 hertz you are talking of 20 milliseconds now the thermal time constant is much longer than the line cycle time that is the fundamental assumption here now.

So, at 50 hertz if you are doing it is very very valid now. So, it does not heat up. So, on in an average sense you know the device losses are reduced now if you are going to do a switching not at 50 hertz, but at something like 0.5 hertz or 0.05 hertz you better be very very careful now. So, this entire thing that you got here the previous one is based on the assumption this bus clamping is based on the assumption then the thermal time constant is longer than the line cycle time if that is not valid you really cannot go in for bus clamping. And in most cases when you are switching you know your modulating frequency is like 50 hertz, 40 hertz, 30 hertz, it is a perfect assumption right. So, we go forward now.

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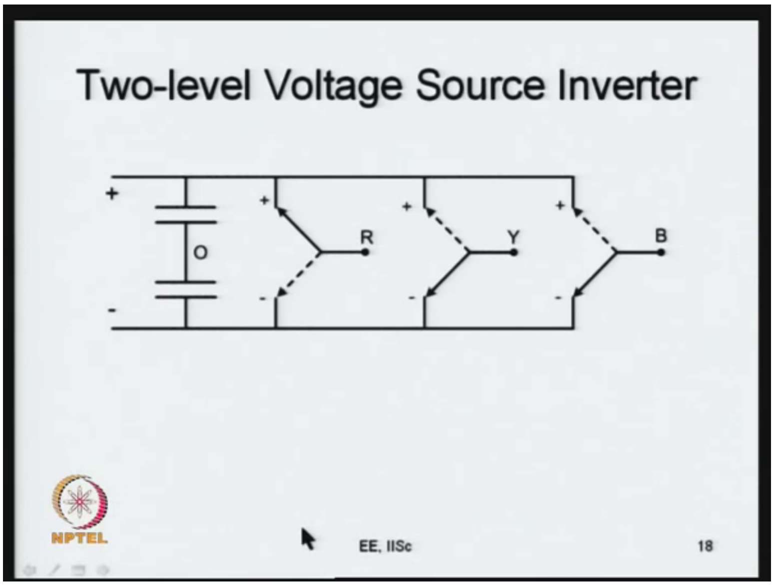

So, what do we do look at a three-phase voltage source inverter now. So, it is the same thing we just dealt with this even harmonic primarily to prime ourselves to deal with this problem of three-phase inverter adding common mode injection or third harmonic injection in three-phase inverter and that is a very significant practical problem it has great theoretical and practical significance. So, we just prepared ourselves by going through single phase inverter which has only 2 legs before we tackle the problem of 3 legs now.

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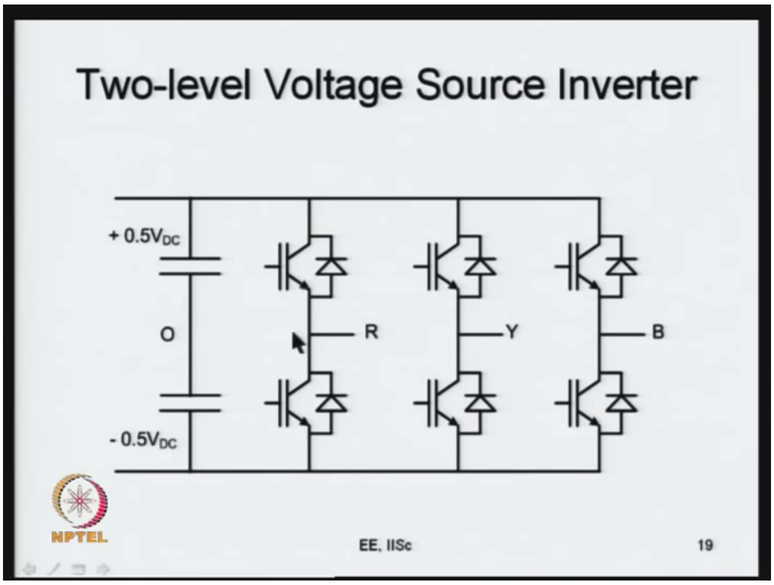

So, you have 3 legs and all the 3 are single pole double through switches and they are realized in terms of switches which switch in a complementary fashion as we know.

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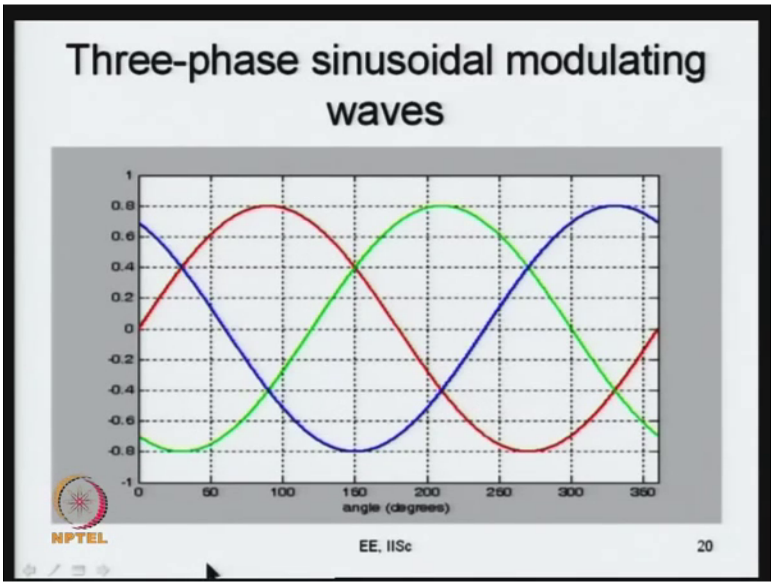

So, what we do now in the case of unipolar PWM for single phase inverter you simply use 2 sine waves which are phase shifted be 180 degrees. Now what we are doing we are using 3 different sine waves and the sine waves what is the frequency of the sine wave it is that output modulation frequency that you desire and what is the amplitude of the 3 sine waves they are equal and how about the phase they are phase shifted by 120 degree each this is the red phase r, this is the Y phase I have just given it in green for clear visibility and this is the blue phase B your phase shift are by 120 degree you will get this Y phase signal your phase shift this by 120 degree you can phase a signal.

So, these are three-phase sinusoidal modulating waves what you could do is you do this you know you can compare this with the high frequency carrier that goes up and down like the arrow that I am showing there right it moves up and down very very high frequency carrier you can compare same carrier for all the 3 modulating signals and whenever the modulating signal of a phase is greater than the caddied you switch on the top device whenever the modulating signal is less than the carrier you switch on the bottom device that is a simple logic as we discussed in the last class now.

Now, once again in three-phase inverter there are redundancies what is the redundancy very very similar to what you had in case of a single phase inverter that is when your load is being shorted you can have the situation.

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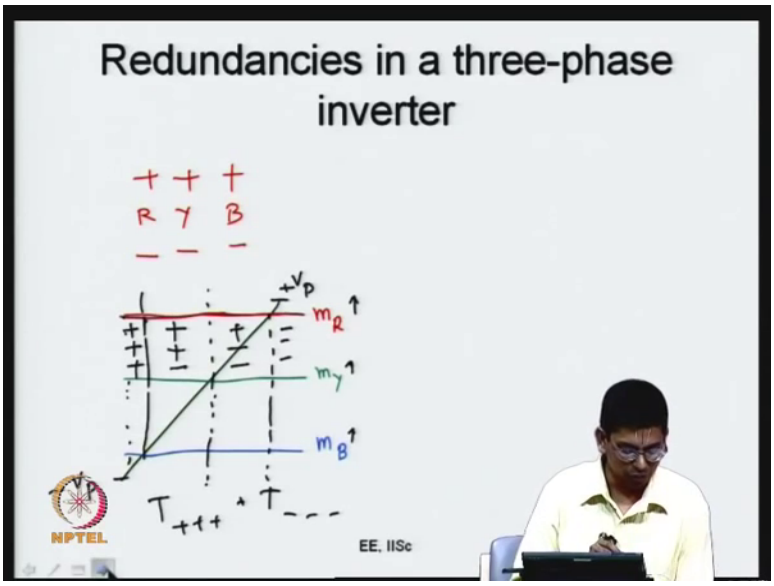

What I would say as plus plus plus what I mean by plus plus plus is R phase Y phase B phase the R phase top device is on Y phase also top device is on B phase is also top devices on all the pole voltages are plus VDC by 2 plus VDC by 2 and plus VDC by 2 what is the difference between those 2 what is VRY 0? What is VYV 0? What is VBR 0? This is what is called as a 0 state the line cline three-phase line cline voltage is 0 you the shorting the load the load is just being in there are only a freewheeling path is being provided for the lower now.

So, it is being done by keeping all the top devices on this is not the only way to do that there is yet another way of doing it what is that you keep R, Y and B in all the 3 legs you have the bottom devices on this is again would ensure the load is shorted in this case VRO, VYO, V BO are all equal to what minus VDC by 2 nevertheless all the 3 line to line voltages VRY, VYB and VBR are equal to 0 the load is shorted. So, the as far as load is same plus plus plus is one inverter state 1 0 state and minus minus minus is another 0 state these 2 are the same as far as the load is concerned, but as far as the inverter is concerned it makes a lot of differences now in this I mean the sense here the top devices are on here the bottom devices are on.

So, in the in the in the first case the top devices are going to be suffering loss on account of conduction in the second case the bottom devices are going to be suffering loss on account of conduction now. So, the normal thing to do is use both the stage that would be the conventional wisdom and also you do it equally and that is what you do in conventional space vector PWM which we will discuss a few classes later now.

So, you will see that this is there is a redundancy the same way the 0 applied there are 2 different states that is possible for you here also there are 2 different states are possible now the poles can be connected all the poles can be connected to the top throw all the poles can be connected to the bottom throw that is how it turns out to be now. So, that is a redundancy now because it is a redundancy what happens now.

Let me take a this thing let me first choose let us say black ink and let me draw a half carrier as I did before now then let me choose red ink and draw the carrier I mean the modulating signal did I choose red the other thing there is a different version of red. So, it is all right this would be proper; this is what I would call as MR, the modulating signal corresponding to R phase in this carrier cycle as I said the carrier cycle is much shorter than the modulating cycle signal cycles therefore, the modulating signal is a flat line here.

Then let me just go and indicate the Y phase signal let me say this is Y phase signal and then there is a B phase signal, let me indicate it with blue. So, like this if mR my and mB are sinusoidal signals then mR my plus mB should add up to 0. So, what you really have here is this is plus VP this is minus VP as before. So, earlier you had 3 different intervals. Now there are 4 different intervals now. So, first there is an interval here this to this during this interval what happens all the three-phases all the three-phases their signals are greater than the carrier signal therefore, what you have is all the top devices are on the inverter state there is plus plus plus you can call that inverter state as plus plus plus and the output is 0 all the 3 line cline voltage is 0.

Then you have a second interval like this during the second interval what happens R phase continues to be high yellow phase also continues to be high, but B phase is now gone negative then there is a third interval during the third interval what happens R phase is high yellow phase is negative B phase is also negative what happens during the last interval all the 3 are minus minus minus this is what happens now once again you can think of a common mode by common mode I mean I would shift mR slightly above my slightly above and mB slightly above and such that it doesnt go beyond VP in this carrier cycle or in any of the carrier cycle, it should not go beyond that that is how I add a common mode signal.

When I add a small common mode signal like that what is going to happen mR shifts up my shifts of mB shifts up therefore, the first interval will longer will get a little longer because mBA shifted up the second the switching instant will delay, but the interval will not change because the difference between mB and mY have an has not changed and similarly the third interval also would not change because the difference mY and mR there is no change in that the difference is still the same when the last interval will shrink. So, the first interval will increase at the expense of the last interval or if the signals come down it will be the other way. So, either the first interval increases at the expense of the fourth interval or the fourth interval increases of the expense of the first interval now.

So, the sum of these 2 if you would call them they that for plus plus plus plus and T minus minus minus I would just call them as time for T plus plus plus on the time for which T minus minus is applied the sum of these 2 is same. So, the during that middle one pulse there is there is some line voltage pulse applied here also there is an line voltage pulse applied and these 2 is on line voltage pulse applied. So, the width of the line voltage pulses will not change, but their positions alone will change now.

So, this is again what you call as a redundancy and this redundancy leads to various modulation methods this redundancy you add some common mode voltage now you can do that 0 state applied that 0 state either they having all the top devices are on bottom devices are on correct and also for longer time you can keep this on or for longer time you can apply this state. So, this redundancy this leads to the application of common mode signal now.

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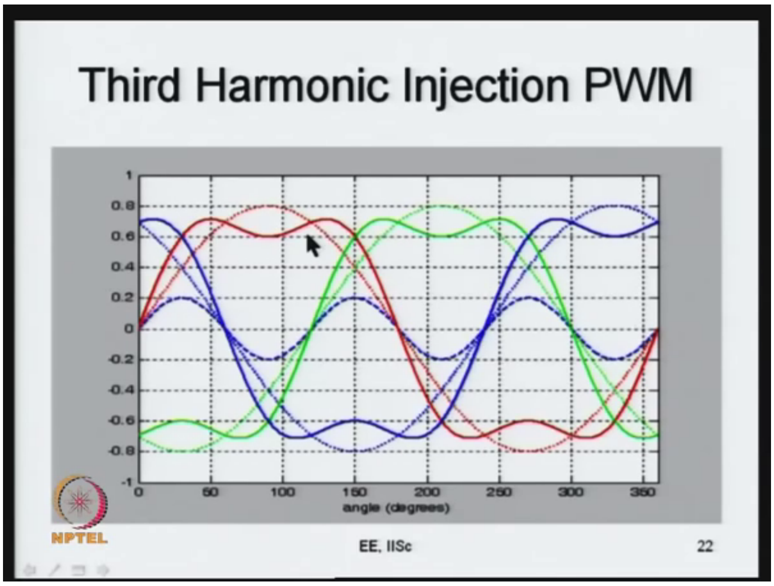

So this is now, what is the common mode signal any third harmonic you had that will be a common mode signal. Now you have fundamental sign that is you have this red dotted line which is the sinusoidal modulating signal corresponding to R phase, then let us say you add a third harmonic indicated by this blue line given in a dash blue line. So, this is a third harmonic now you add this to mA to get what you call as mA star you see this signal is like this where the head has gone up it is like a bent head it has gone inside. Now where the original sinusoidal signal had a peak is going out this is slightly come down and you can see that the new signal has a lower peak value than the original signal now.

So, when I produce such an mB m R and if you wave shift by and 20 degree the sinusoidal the fundamental sinusoidal component is shifted by 120 degree, but the third harmonic component is unshifted because third harmonic wave shifted to 180 degree it means at the fundamental frequency the third harmonic frequency is simply shifted by one cycle time. So, you add the third harmonic to mR and my and you subtract the 2 the third harmonic will vanish just as the second harmonic vanished there now.

So, what you can now do is you can add such a small amount of the harmonic there and now with this third harmonic addition what you can do is you get these signals the red signal and then you see this green signal which represents the yellow phase and you see this blue signal that represents the blue phase this can be compared against a common triangular carrier you may say what is the point in doing so.

Now you see this red signal the original dotted signal has a higher peak, but second signal has a lower peak value and the lower peak value is what limits the end of linear modulation that is earlier this peak could go all the way up to one now, because of this addition this peak could go all the way up to 1 by the time this lower peak goes to one, you can certainly see that this dashed aligned peak the original sine wave peak would have gone much above one somewhat above one. So, that actually means it is possible for you to produce a higher fundamental voltage with this then you can do without sine addition now.

Let us demonstrate this now I can write down a few equations here.

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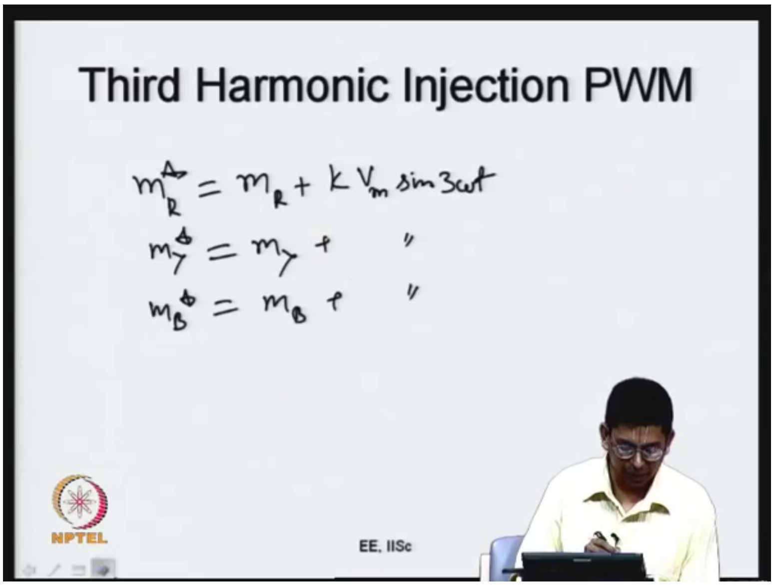

So, if you write down the equation what I am trying to do here is I am take mR mR star equals mR plus K times mR I am sorry mR is Vm sine omega T K times Vm sine 3 omega T I can again say my star equals my plus the common mode component which is ditto mB star is equal to mB which is the sinusoidal signal plus the same thing. Now this is what you do and this K is a it can be varied you know K is a small number you can take it as 0.15 percent whatever K equals one sixth is what would give you the best DC bus utilization that is it is good to produce I mean high amount of AC voltages with whatever DC you gave, but something we will discuss a little while now.

So, this is the third harmonic injection that is K is equal to 1 by 6. Now I am showing it with K equals 1 by 6.

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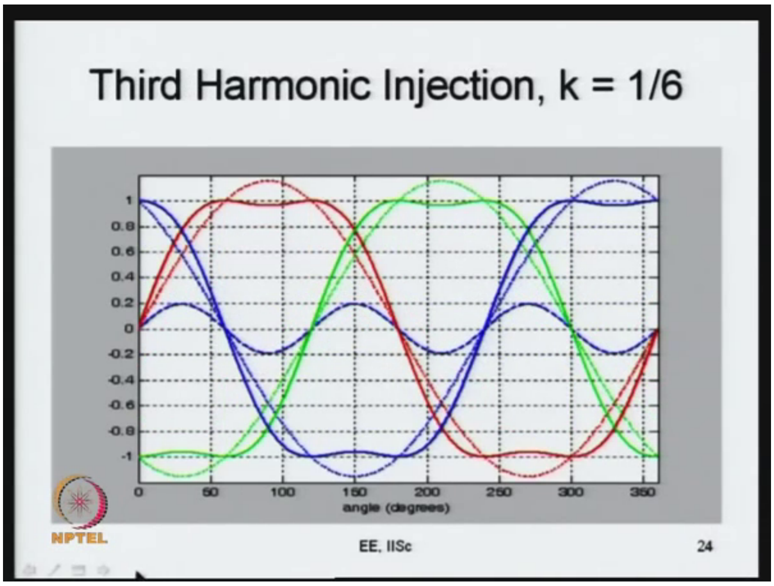

So, you see what happens I am showing the red original sinusoidal signal the original sinusoidal signal goes clearly above one what I have taken as actually one 0.15 or. So, that is basically 2 upon root 3 this is 2 upon root 3 is the original sine wave now and to that I am adding a third harmonic component whose amplitude this blue thing the amplitude of this blue wave is one sixth of the red dotted wave when I add like this what I get is the resultant is what I get here.

So, I am able to move up to 2 by root 3 my peak of the sine is not limited to one, but it can go all the way up to 1.152 by root 3 or 1.15. So, it gives me 15 percent additional voltage with the same DC bus voltage if I modulate my inverter using such third harmonic injection whose where the third harmonic amplitude is 1 by 6 times the fundamental amplitude I can produce 15 percent more fundamental voltage AC voltage with the same DC bus voltage and same inverter now that is one advantage now.

So, it is leg B you are you are increasing the voltage rating of the inverter you know without really increasing the voltage rating of the devices that you are really using that and use you can see the benefit there now and this third harmonic injection also influences the spectral properties the PWM waveform ultimately if you produce and you compare the spectral properties differ with this third harmonic now and instead of K equals 1 by 6 if you take K equals 1 by 4 that gives you very good spectral properties and that is very very close to what is conventional space vector PWM which we will discuss a little later now.

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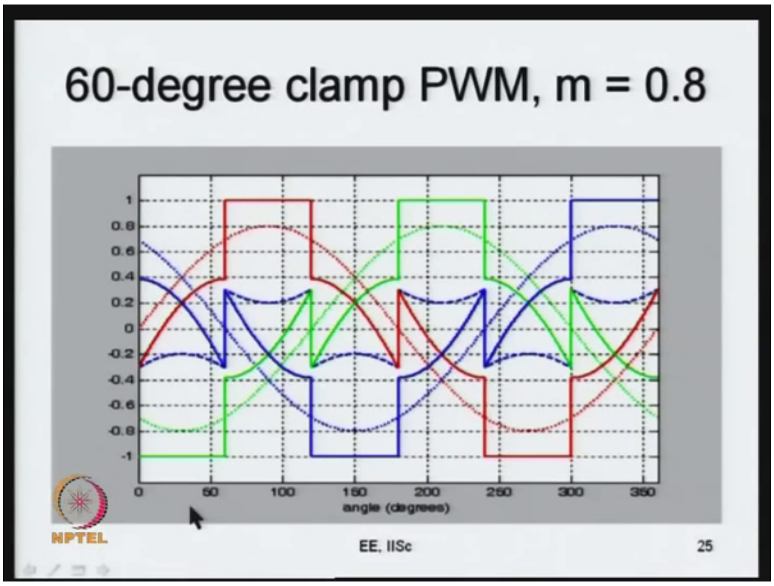

So, here also what you do is the same way that we did there you can add all triple in frequency components not only third you can add third ninth 15th and all those components you can go about adding correct. So, how do you do that and you can add them in such a fashion that there is bus clamping. Now what I am trying to do is you see this blue signal do you see this signal this is common mode, I am getting it by subtracting different modulating signals and different regions from either plus 1 or minus 1. Now when I add this common mode signal what happens I get a resultant waveform like this you see the red waveform. So, it is clamping here it is not clamping for 90 degrees as it happened in the single phase case where there are 2 legs it is clamping for 60 degrees now.

The same R phases is clamping for 60 degrees and then negative half cycle. So, here the positive top device would be conducting here the bottom device should really be conducting now. So, this is what you do say I mean whatever conduction level there is a uniform distribution between the top and bottom devices now and all the 3 modulating signals are also phase shifted versions of one another this also this is a kind of bus clamping that ensures equal loading of all the devices that we were discussing in the single phase case now. So, this is 6 degree clamping. Now we will discuss this in greater detail in the next lecture where we will essentially deal with clamping, but just let us a kind of familiarize ourselves with various kinds of thing now.

Now, the same 60 degree clamping you can go all the way up to 2 by root 3 instead of one I am going up to 2 by root the fundamental amplitude and now you see that my common mode signal looks different. Now if I add this common mode signal this is the kind of modulating signal I get and you know without going into over modulation or pulse dropping I can get. So, I can get this 15 percent higher voltage here also and what happens besides that is there is a reduction in the switching loss that something that I am able to achieve now.

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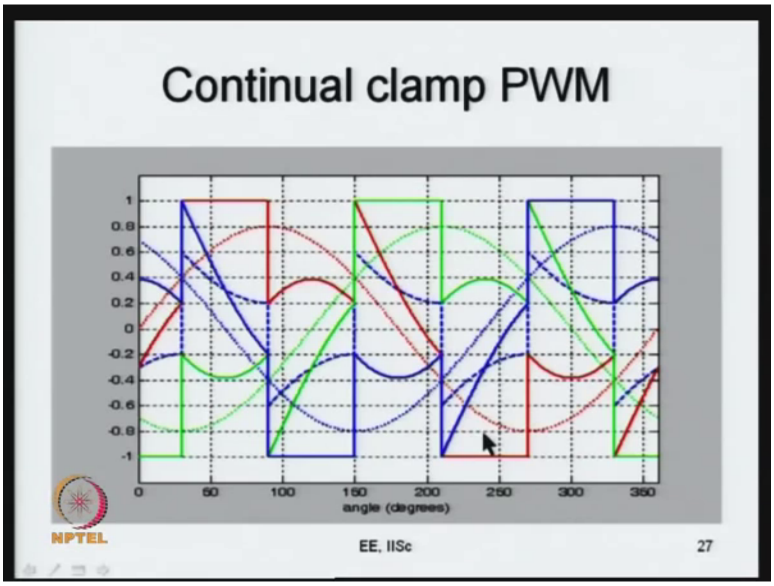

So, there is a generalized version of that here you see that the clamping is in the middle 60 degree duration, it does not have to be in the middle 60 degree duration that can be shifted to the left or right anywhere between 30 degree to 150 degree which we will discuss further with the continuous class now. So, this clamping instead of being from 60 to 90, it can be between 30 to 90, 40 to 100 or you know even 90 to 150.

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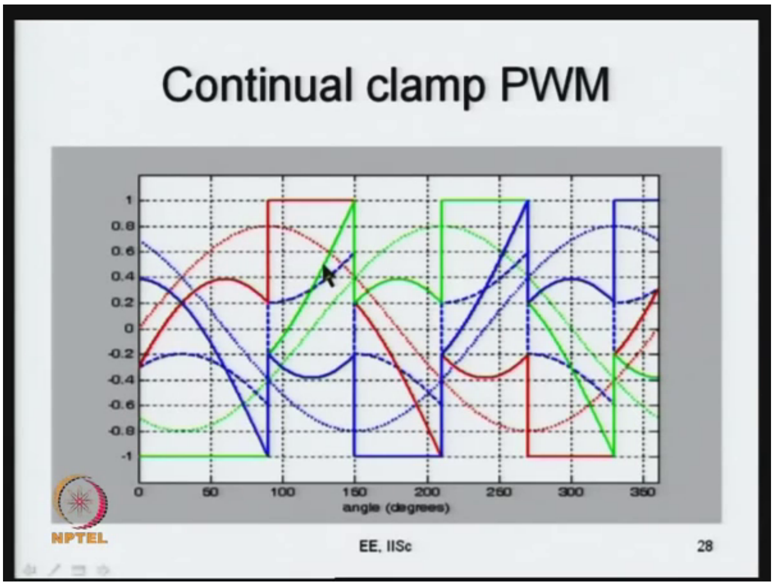

So, it you can clamp it for 60 degree duration anywhere there is on the position of the clamping interval can be changed and they change it normally for depending on the load power factor to reduce switching loss which we will discuss a little later. So, this is continual clamp PWM now.

What is also possible is split clamp PWM. So, instead of clamping it continually for 60 degrees it is also possible for you have to clamp the 60 degree duration into 2 different intervals say for 30 degrees in the first quarter cycle and 30 degrees in the next quarter cycle and so on. So, this continual and split clamping PWM would be the subject of our next lecture. So, this is what I am trying to look at now.

So, I hope that you know you have been fault. So, what we have tried to do is introduce the concept of even harmonic injection in the case of single phase inverters now it does not have any practical benefit really speaking there is no increase in DC bus utilization you really cannot produce higher AC voltage. In fact, the AC voltage you can produce will become lower if you inject even harmonic. So, in that sense even harmonic injection is disadvantageous in the case of single phase inverters.

On the other hand, you can certainly go in for bus clamping that is bus clamping if you do you will be able to reduce the switching loss and that has been discussed in this particular reference that I am showing here.

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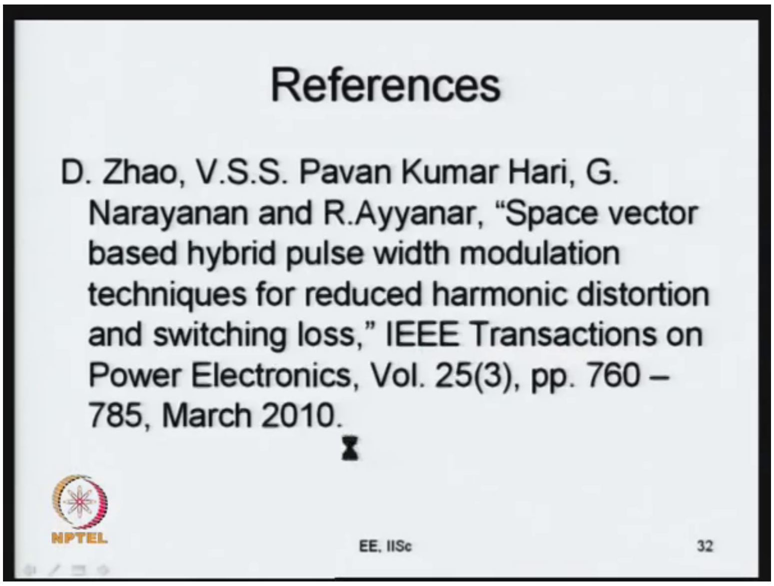

Which is the second reference that you see here; we have Patnaik at L; let us an investigation into even harmonic injection.

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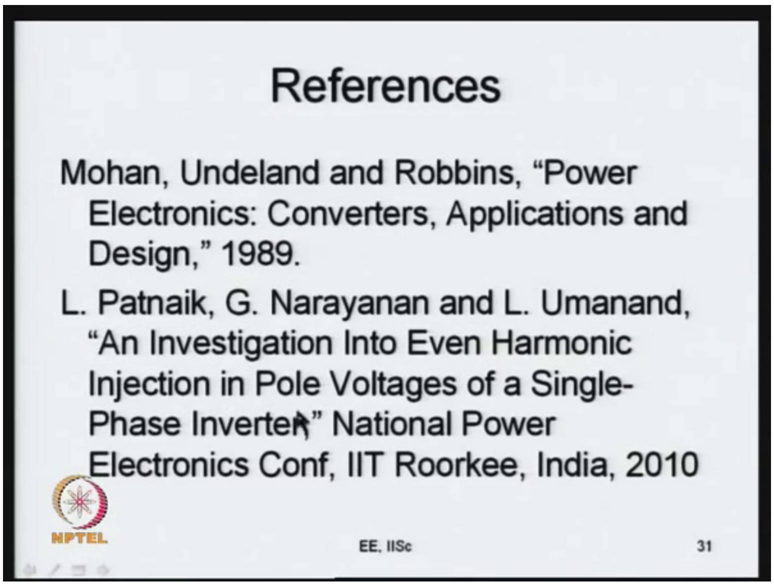

And pole voltages of a single phase inverter. So, you can get more details of this there.

On the other things are available in this third reference now there is some amount of discussion on continual clamp and split clamp PWM. And we will discuss this in detail in the next lecture. So, thank you very much for your interest in this course and I hope you will continue to be interested.

Thank you very much. Bye.