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

Lecture – 23
Harmonic analysis of PWM techniques

Welcome back to this video course on Pulsewidth Modulation for Power Electronic Converters.

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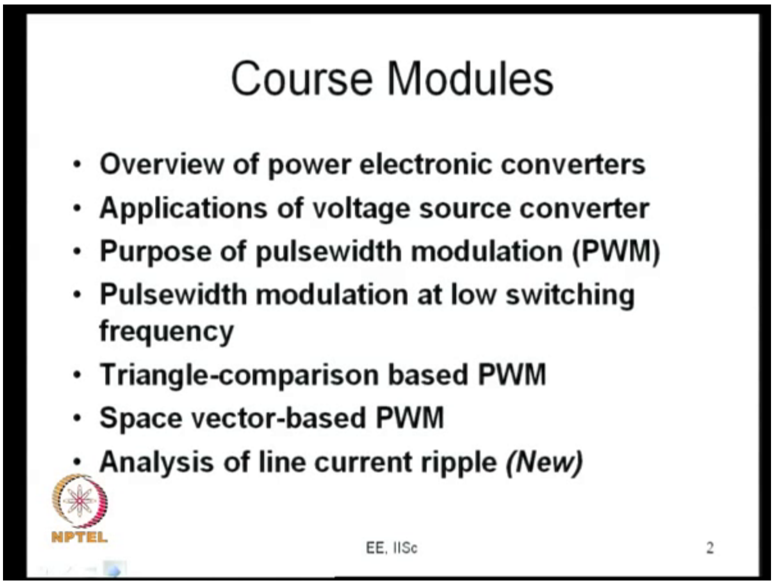

So, we have been covering you know several different modules like the very first module we covered was on overview of power electronic converters and varies the DC DC converters and voltage source and current source converters and multi level converters and so on. And then we specifically looked at the applications of voltage source converter, then we looked at the purpose of pulsewidth modulation and then we looked at particularly PWM at low switching frequencies and from this point onwards we have been we have moved to fairly high switching frequencies, we have been considering switching frequencies which are much higher than the fundamental frequency.

So, this is the first these are very commonly used approach triangle comparison based PWM that is we use set of three-phase modulating signals and compare it again common triangular carrier to produce PWM signals and this is what is triangle comparison base PWM. So, we discussed this in one of the modules. And subsequently we discussed an alternative way of PWM generation which is the space vector base PWM. So, we produce PWM on this using this notion of space vector and we also looked at how these two are the same and also these two are different that is what is common and what is different between these two.

So, we observed that you know whatever PWM waveform can be produced by the triangle comparison can also be produced by the space vector PWM, but certain PWM methods certain PWM waveforms generated by space vector cannot be done using triangle comparison. That is we said that space vector based PWM is more general than triangle comparison based PWM and the specific example is advanced bus clamping PWM that we have here. So, which is possible through the space vector approach and not possible by comparing this triangle you know the other way of doing it.

So, after this we are now getting started. So, these modules the two modules focused on how do you generate the PWM signals and now we are beginning to understand you know do some analysis on how you know how much is the destruction that is caused and so on. So, this is about PWM generation here we are getting into analysis. The first kind of analysis that we will be doing is we will be looking at the line current ripple. That is the output waveform what you are producing is not perfectly sinusoidal there are sinusoids and also there are harmonics added to that and because of the harmonic components in the voltage that are going to be harmonic components in the current and therefore, there is going to be a ripple in the current over and above the sinusoidal current, the line current does not going to be purely sinusoidal on top of it there is going to be certain amount of ripple. So, analysis of this line current ripple is what is the new model, which we are going to be discussing over the next 4 lectures including the present one.

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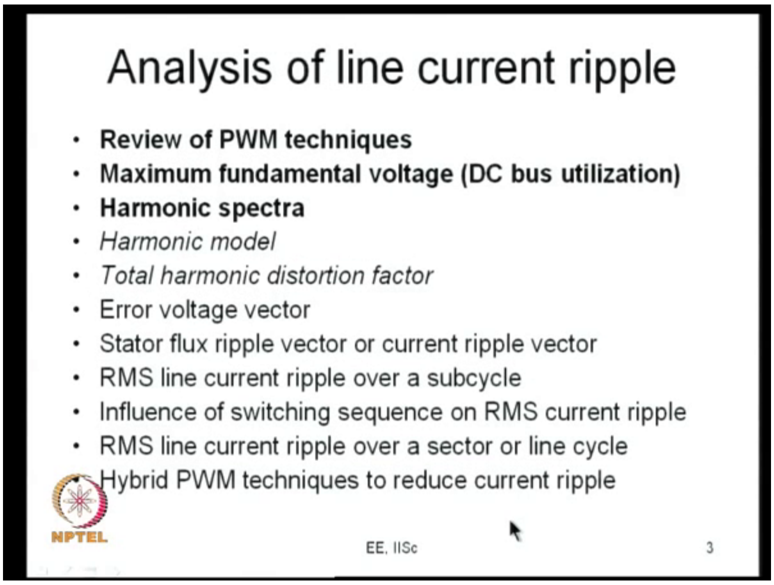

So, we look at this analysis of line can triple what is it that we would do in this is you would do a review of various PWM techniques which we have covered in the last about 8 lectures or so on, we would take as we progress we will review them also and we would look at the maximum fundamental voltage that is possible with a given DC bus voltage that is let us say have a fixed DC bus voltage of 600 volts or so, how much is the maximum line voltage that you can produce it slightly changes from 1 PWM method another the PWM method.

So, as we you know that something like on what we can call as DC bus utilization. So, we would look at that that is one of them. And you look at the harmonic spectra the fundamental component is one of the harmonium one of the frequency components if you look at the PWM wave forms it would have the fundamental and it lots have a lot of harmonics you may try to get some understanding of the harmonic spectra. So, for example what frequencies would you expect the harmonic components to be and so on. And once you have harmonic spectra there are harmonic voltages we need to understand the effect of these harmonic voltages what you know what is their effect what is their influence on let us say a motor that is being real. So, that is why you would have a review on the harmonic model also and we would look at the total harmonic distortion factor so on so forth now.

So, this part of the work primarily that is today’s lecture what is given in bold is more from the frequency domain point of view you would try to understand what are the various frequency components in the PWM waveforms and what would be their influence and so on so forth now.

In the subsequent lectures in this module from next lecture onwards we will start looking at it in from a different point of view that is you know error voltage vector, that is we will start looking at it from a space vector point of view the PWM waveform is the three-phase PWM waveform you know it is there are three-phase voltage is basically getting applied on the motor the three-phase voltage can be seen as a voltage vector and you have the desired voltage vector to be applied and we have the actual voltage vector that is being applied. And there is a difference between the desired voltage vector and the actual voltage vector then that is what is called as the error voltage vector.

So, we would look at the error voltage vector now. In a different way if you look at it you have harmonic voltages right you have fundamental voltage you have harmonic voltages you have harmonic voltages in all the three-phases now. So, you can call them as voltage ripple the sum of all harmonic components you can call them as voltage ripple. Now transform the voltage ripple in the three-phases into a two-phase quantity into the space vector domain and that is error voltage vector. So, error voltage vector is the space vector representation of the voltage ripple I mean, by voltage ripple I mean the actual voltage minus the sinusoidal the desired sinusoidal component.

So, you can look at it as error voltage vector and what you can do is you can integrate that error voltage why do we mean by integrating this harmonic model the harmonic model of an induction motor is basically its leakage in difference we have seen this in one of the lectures before and you take a quick look at it again today. So, now, if you apply a voltage across an inductor the current is going to be proportional to the integral of the voltage and therefore, we will integrate this error voltage vector and that gives a quantity called stator flux ripple vector because its voltage you integrate that it is going to give a quantity whose dimension same as flux and these voltages are actually applied on the stator of the induction motor and therefore, if you integrate them that gives the kind of the stator flux ripple.

So, you recall the state of flux ripple vector and this is equivalent to the current ripple or its current ripple vector. So, if you scale this appropriately you get current ripple vector now and the current ripple vector is nothing, but the three-phase current ripple transformed into the space vector domain. And what do you mean by current ripple? It is a non sinusoidal part in the current waveform the current has a sinusoidal component of the desired frequency plus it has harmonic components, the sum of hall harmonic currents we call it as current ripple and the current ripple in the three-phases can be transformed into a vector and that is what we call as current ripple vector right. And based on this analysis what we will do is we will try going into the study of line RMS line current ripple over sub cycle, we will try to find out you know how to get this RMS line current ripple over a sub cycle which is a small unit of time and we would try and study the influence of switching sequences on this RMS current ripple.

So, how instead of one switching sequence we is let say in the conventional space vector PWM we start with one particular sequence we start from the 0 state and go to 1 active state another active state and come back to the I mean we go to the other act 0 state. So, like 0127 instead of that you can use a different switching sequence as on bus clamping PWM where you use only 1 0 state or you can use a switching sequence as an advance bus camping PWM where 1 phases clamped second phase which is one. So, we will have third phase which is twice. So, there are different switching sequences which we discussed in the last couple of lectures and we would look at the influence of these switching sequences on the RMS current ripple now right. So, then these RMS line current ripple over a sub cycle you can use that and you can kind of integrate the mean square ripple to get the RMS current ripple over a sector or line cycle this is what we will do.

And this is kind and we use all this idea this is about the analysis and the last part is about designing. Once we understand how the sequences influence the RMS current ripple it is possible for us to design a hybrid PWM method that is a combination of different switching sequences and you know which we will lead to a reduction in current ripple. So, we will look at this as on the last lecture in this particular module. So, this is what we are planning to look at in this particular module. So, today primarily our emphasis will be here we will be looking at more from the frequency domain point of view we will try and understand the harmonic spectrum here and the effect of the harmonic voltages also on so forth.

So, specifically I would call this as harmonic analysis of PWM technique that should be the lecture today.

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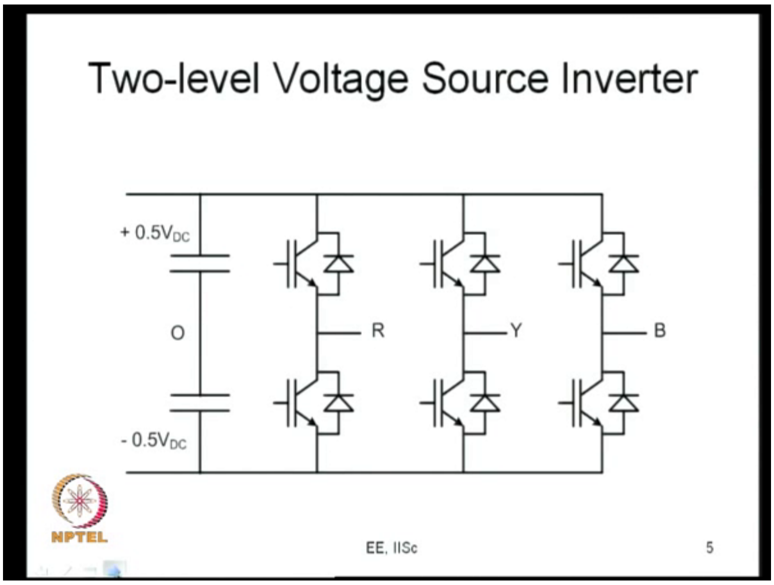

And you know what we have been talking enough is a 2 level voltage source inverter. So, it is a DC and it produces AC it is an inverter its produces three-phase AC it is a three-phase inverter and it is a 2 level voltage source inverter. So, if you take the R you know this is the pole I mean this leg is a single pole double throw switch the top is on R the bottom is on such a single pole double throw switch the pole is connected to either the positive voltage or to the negative voltage and there are 2 levels and therefore, this is a 2 level voltage source inverter. And the kind of load that is connected between R Y and B here, R Y and B is shown here.

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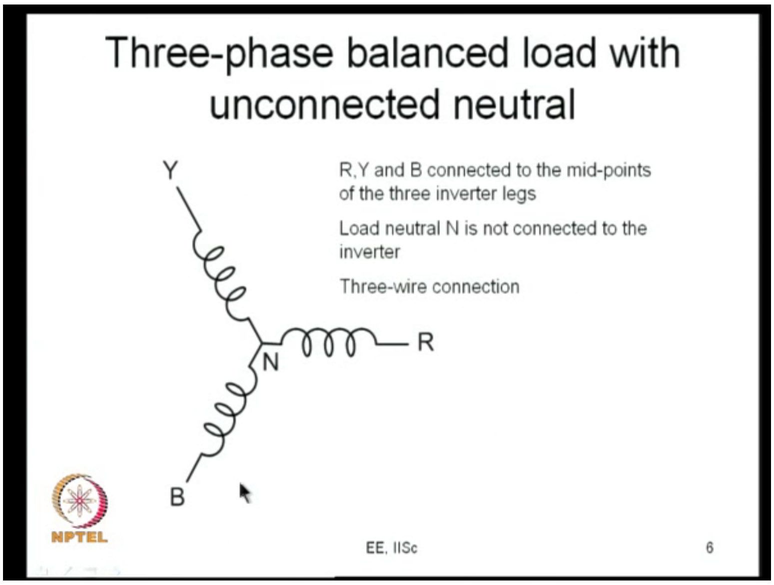

So, you know this is a typical kind of load that we have. You can probably regard this as a stator winding of a machine. So, R is connected to the midpoint of R phase leg why mid phase leg and B is to that midpoint of that leg and N was the load neutral this is not particularly connected anywhere else, but through the R Y and B.

So, we are talking of a load neutral is not connected we are talking of basically a 3 wire connection it is a three-phase 3 wire connection right.

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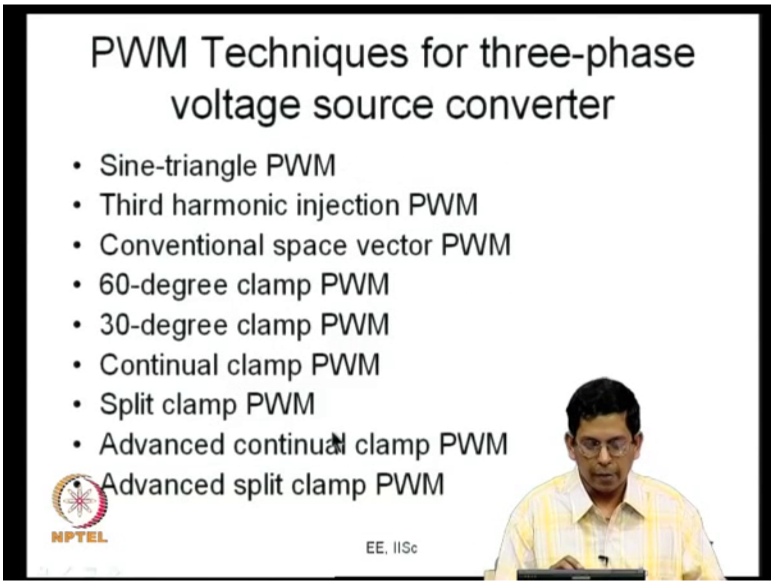

So, a quick list of the PWM techniques that we have looked at in the last couple of modules. So, sine triangle PWM is the most popular PWM method you use three-phase sine waves you compare them against a command triangular carrier and the you produce the PWM signals right.

So, to the sine waves you add third harmonic component when compare them with the common triangular carrier and, this is third harmonic injection because third harmonic component has been added to the three-phase sine waves now this is other kind of pw method we looked at now. And you know if you go in for a slightly different kind of common mode injection you would reach the conventional space vector PWM and this can also be produced from the space vector domain which wave like it all right. So, this is conventional space vector PWM and we found that you know and then we looked at 60 degree clamp and 30 degree clamp PWM these are bus clamping PWM or discontinuous PWM methods.

So, in 60 degree clamp PWM you have a phase clamped during the middle 60 degrees in every half cycle and in 30 degree clamp PWM you have a phase clamp during middle 30 degree durations in every quarter cycle and continually clamp PWM is a generalization of 60 degree clamp PWM. The phase is continuously clamp for 60 degrees, but not exactly at the middle of the half cycle that is if half cycle from 0 to 180 degree, in 60 degree clamp the clamping period is between 60 to 180 degree whereas, in continual clamp it can be anywhere between 30 to 90 or 90 to 150 degrees. So, that is continual clamp PWM and you also have split clamp PWM that is the generalization of 30 degree clamp PWM. In 30 degree clamp PWM a phases clamp for 30 degrees in each quarter cycle in the first quarter and second quarter every half cycle.

In split clamp a phase can be clamp for a duration gamma in 1 quarter cycle in 60 minus gamma in the other quarter cycle gamma is equal to 30 is a particular case that will take you to 30 degree clamp PWM. And all these methods the first two are normally generated based on the triangle comparison approach, but if you want you can also produce these waveforms from the space vector approach right that is also possible to do that there. And then you can look at this conventional space vector PWM this can be produced from the space vector point of view it can also be easily produced by adding certain common mode component as we discussed in one of the previous lectures now.

Again all the 60 degree 30 degree clamp and their generalizations for called continual clamp and split clamp all these PWM methods can be all these PWM waveforms can be produced either using the triangle comparison approach or the space vector approach the last two that we are talking of here can only be produced using the space vector approach.

So, these use some of the flexibilities that are offered by the space vector approach namely that of dividing an active vector time what all these PWM methods do is to divide the null vector time. The divide the null vector time that is T Z between the 2 0 states which is minus minus minus and plus plus plus and what this does is it uses this deviation of null vector time it is like bus clamping PWM uses only 1 0 state to do that you know it do is on top of it uses this division of active vector time these methods they apply an active vector more than once in a sub cycle. So, they are we, we call them as advanced bus clamping PWM method explicitly the advanced continual clamp and advanced split clamp PWM.

So, we would look at you know the how the frequency spectra would look like in many of these cases get some idea of the frequency spectra in today's lectures now today.

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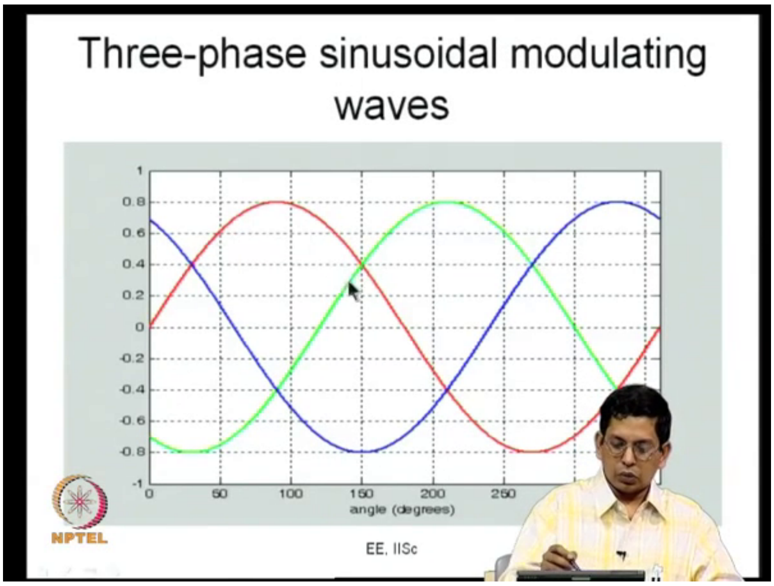

So, this is now you have your three-phase sin R Y and B which are like 1 and minus 1 stand for the positive peak and the negative peak of the triangular carrier and, you compare this with the triangular higher frequency triangular carrier and do you produce the PWM wave forms which are used to switch the inverter fine.

So, how would the harmonic spectrum look like that is the question now. So, if you go back what are the various frequency components here one is the fundamental frequency this is what you can call as f 1, on the other one that I am not shown here is the high frequency carrier which can be at a frequency what we can call as f c.

So, now let us see what how this should be look like.

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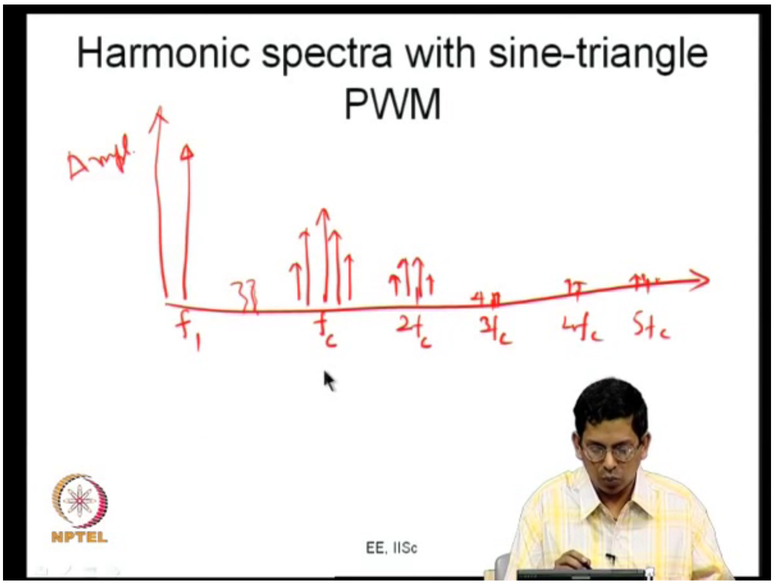

So, I want to look at the harmonic spectrum this is frequency on the horizontal axis and amplitude on the vertical axis. So, what you will certainly have is you will have a fundamental component, you will have a fundamental component let me call this as f 1 this f 1 is same as the modulation frequency.

So, if you are using the low switching frequency PWM which we were discussing earlier this is f 1. Now you will also have this is a 50 hertz you will also have 250 hertz, 350 hertz components 5th 7th harmonic we will have 11th and 13th harmonic here you will not have all that because your carrier frequency is quite high. So, I will draw break here this is a break.

And now let us say you have a switching frequency you have this carrier frequency which we call as f c and then let us say you have the stoop twice the carrier frequency 2 f c now what we will have is you will have some harmonic components here you will have some harmonic components around the carrier frequency f c. And again you will have some other harmonic components around the carrier frequency 2 f c something like this. And it can actually go on let me extend the line little further. So, now there is also around 3 f c, there is also around 4 f c and 5 f c you will have components are on this harmonic components are all these things. So, the components around you know 3 f c 4 f c etcetera as the higher and higher frequencies go you mean the amplitudes themselves might reduce. Normally I would say that these 2 components around f c and 2 f c are quite dominant.

So, what you have is you have a fundamental component and you have several components which are called switching frequency components and there is a big separation in the frequency between these two sub separation this can be 50 hertz and this can be 5000 hertz. So, you see there is a 1 is to 100 difference now. So, the many a times what happens is the machine model you know it is the load model itself is different for this in that. So, many a times the reactance offered by the machine itself is substantially high for these kinds of frequencies the just the leakage reactance itself is fairly high and you know these components get very nicely at innovated that is though there the considerable harmonic voltages apply harmonic voltages of considerable amplitude are applied the corresponding harmonic currents will be quite low. So, that is the point that I am trying to tell you here know right.

So, there is a very good separation between the fundamental component and the carried component because you are using very high frequency carrier signals now. This is only to get a feel for how the PWM spectrum would look like now. So, to be just get more into the specifics it would suggest that what are this.

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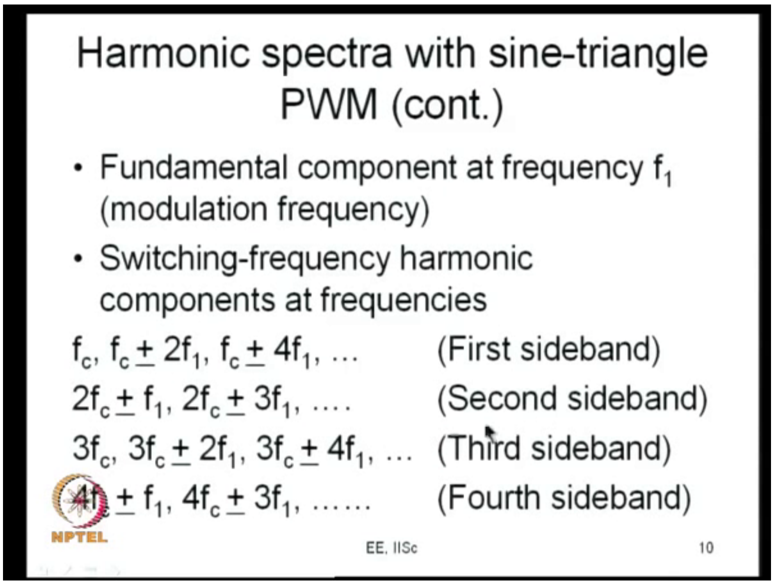

So, there is what you have here is you have the fundamental component frequency f 1 which is a modulation frequency then you have the switching frequency harmonic components now. And the switching frequency components you look at here this around f c you can call them as first sideband and there are components around 2 f c you can call them as second sideband, third sideband, fourth sideband, fifth sideband and all that.

So, I would normally say that the first two sideband should suffice because the third 4th few sidebands might be their amplitudes might be lower than those of the first and second sidebands. And further we there is also reactance you have the there is a filtering effect this is the machine is you know seen as the leakage, inductance the leakage reactance seen by this and the leakage reactance seen with this are very high the leakage reactance seen by the fifth harmonic sideband are 5 times the leakage reactance it by the first sideband harmonics.

So, from that point of view also the higher side bands are negligible. You would normally have to consider only is about two sidebands here and the actual frequencies are something like this here this is the result of the modulation process the switching frequency components you will see the first sideband and the first sideband is around f c, f c plus or minus 2 f 1 f c plus or minus 4 f 1 etcetera the second sideband you will get it as 2 f c plus or minus f 1 2 f c plus R minus 3 f 1 so on. And the third sideband you will find them around 3 f c 3 f c plus or minus 2 f 1 3 f c plus or minus 4 f 1 and so on and that we would call as the third sideband and 4 f c plus or minus f 1 4 f c plus or minus 3 f 1 etcetera that would call the fourth sideband.

As I mentioned before that the first two sideband should actually be a you know enough for us to kind of have a reasonable estimate of that, but for a better estimate value can always go to you know consider more number of sidebands here now.

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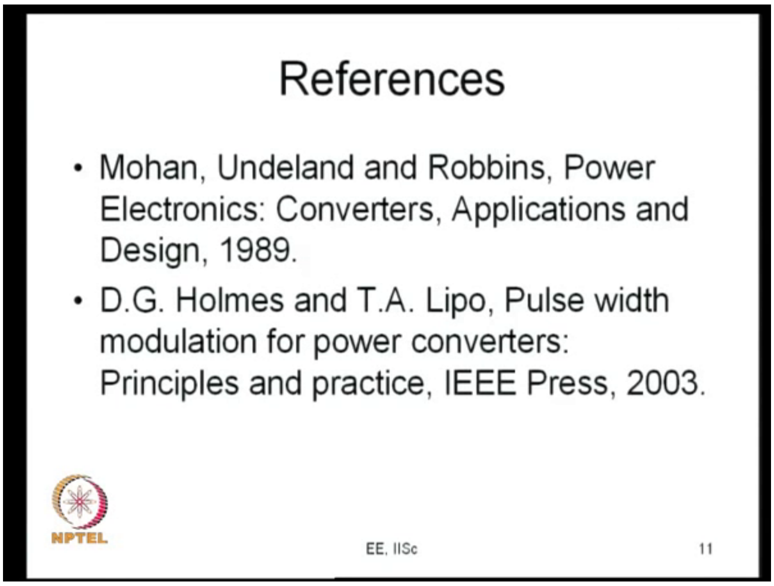

So, I would give you this reference for further information on these things that you could refer to Professor Mohan's book power electronics converters applications and design that gives a discussion on these harmonic components with the sinusoidal PWM and I have not been discussing the amplitudes of these components now.

So, what are these amplitudes going to be that is an important question and you can find that in this book by processor Holmes and Lipo on pulse width modulation for power electronic converters which I have mentioned in a number of times before in this lecture. And these components are actually you know the amplitudes are determined using what is called as double Fourier series and that is out of scope of this course we will not be discussing this what would be this exact amplitudes it is possible to calculate using double Fourier series you can look at this ho Holmes and Lipo book are several other published papers in the literature which talk to you about that. And we will not be doing that for one reason that is we would try and keep our you know we will stick will not get into details that is one reason. And what is important is see every frequency component for example, this particular frequency component is going to drive a current a harmonic current of the same frequency and this particular component is going to current of a particular frequency now.

So, all these harmonic currents can be added up and they get you an RMS current this an RMS ripple current what we are interested in many situations is to find out what is your RMS current ripple. So, we would take the root of space vector approach and we do some analysis based on the spacer to approach and try to come up with what is the RMS current ripple, hence we will not go into what exactly are the amplitudes of these various components. And normally we would probably look at what is the dominant component the first sideband and what is probably the dominant component in the second sideband and. So, the details as I told you can look at these two books and particularly book by Holmes and the Lipo for many details regarding double Fourier series and analysis of the spectral waveforms and sine triangle PWM and quite a few other related PWM methods now.

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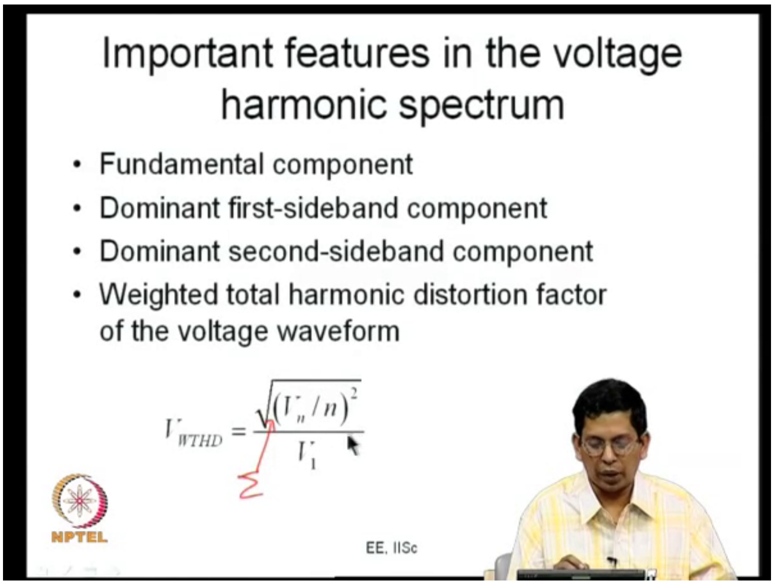

We will just focus on the important features in the voltage harmonic spectrum. So, what are the important features there? One thing that you certainly cannot misses fundamental component this is the purpose of pulse width modulation now the purpose of pulse width modulation what you cannot avoid are the harmonics there are several harmonics or there are various frequencies they have various amplitudes. So, whereas, number of sidebands as I said we will consider the first and second sideband and there also we will look at the dominant component at the first sideband that tells you how bad the first sideband is and you can look at the dominant component in the second sideband that tells you how bad the second sideband is and in many PWM methods interestingly it would be either the first sideband or second sideband that will be dominant at different ranges of modulation index.

In conventional space vector PWM for example, you know the second sideband will be dominant in low modulation indices and at high modulation indices it will be the first sideband that becomes dominant now and that is the reverse in case of advanced bus clamping PWM as I will mention a little later on this knob. So, what we would say is the important features when you look at the important features well one can argue about this is to what is important what is not important we just trying to get a grasp or that there are non idealities all the harmonics are non idealities in the waveform we want to understand you know how significant or how big it is so on.

So, you know you can probably look at the first two sidebands in the dominant components the two sidebands to get a measure of how bad the waveform could be or I know what its quantity or so on. And the other component of if you this very quantitative component which gives you more detailed picture of the harmonic distortion is the weighted total harmonic distortion factor of the voltage waveform what we are having is a voltage waveform. So, what we have is and it has an harmonic component which we can call as V n the nth harmonic. So, that V n by n the whole squared for all n you know that is it is that exist in that except for n equals 1 all the harmonics like 5th 7th 11th 13th and all of them are added up there should be a sigma sign here. I mean please excuse me in please include a sigma sign here. So, you should have a sigma of this.

So, V n by n squared would simply mean the nth harmonic alone this is sigma of all of that divided by V 1 this is what is called, so this V n by n the whole square is a measure of a particular harmonic sigma of V n by n the whole square is a measure of all the harmonics and that is normalized with respect to the fundamental voltage to give you the weighted THD of the voltage waveform. We will again discuss this a little later as to why we are looking at this like this now. So, what is V n is the nth harmonic and V n is being divided by N why is it so, that is because of the motor model which is what we are going to look at now.

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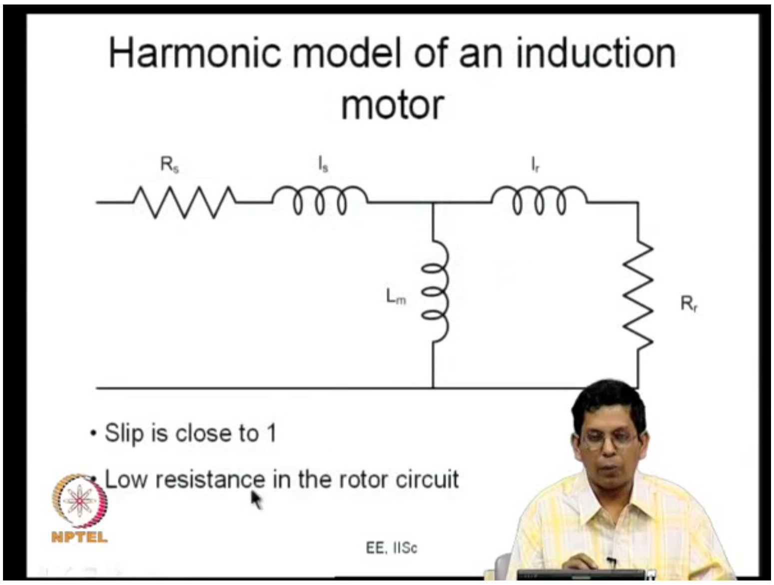

So, let us say this is something we looked at in one of the previous lectures also, but I am just doing a quick recap of that. So, you are what harmonic model of an induction motor now let us say the fundamental voltage is applied and there are different harmonic voltages are also being applied let us consider a particular harmonic voltage being applied now. So, this is the model you know like I mean for an induction motor at steady state balanced and when sinusoidal voltage is fed now.

So, this now this the sinusoidal frequency is very high we are considering harmonic component now and what we have is this slip R r by s is actually R r by s. When you when you consider the harmonic you know the harmonic frequency is much higher than the rotary speed therefore, the slip of the rotor is very close to 1 as I mentioned in a previous lecture and therefore, this R r by s is simply equal to almost R s is usually a small number for the fundamental component and therefore, R r base will be very big on the other hand here R r basis very small now.

So, what we have is a small rotor resistance in series with the leakage inductance and that comes in parallel with the magnetizing inductance. You know the resistance on the inductance in the rotor circuit is much lower than that of the magnetizing inductance.

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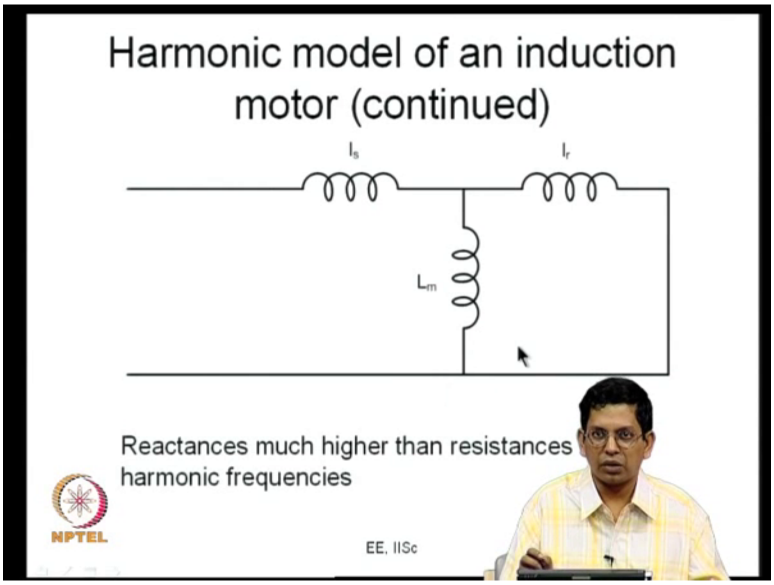

On the first the rotor resistance is low and therefore, you can neglect that and that too at high frequencies the reactance the harmonic frequencies or high frequencies the reactance is much bigger than the rotor resistance. So, you can certainly you can neglect that.

Once you do that what happens is this is the kind of circuit that you are going to get you can use the same argument for the stator resistance also, the stator leakages much greater than that and therefore, you can ignored that. Now what we have is you have this leakage inductance of the rotor coming in parallel of the magnetizing inductance this is large and this is small.

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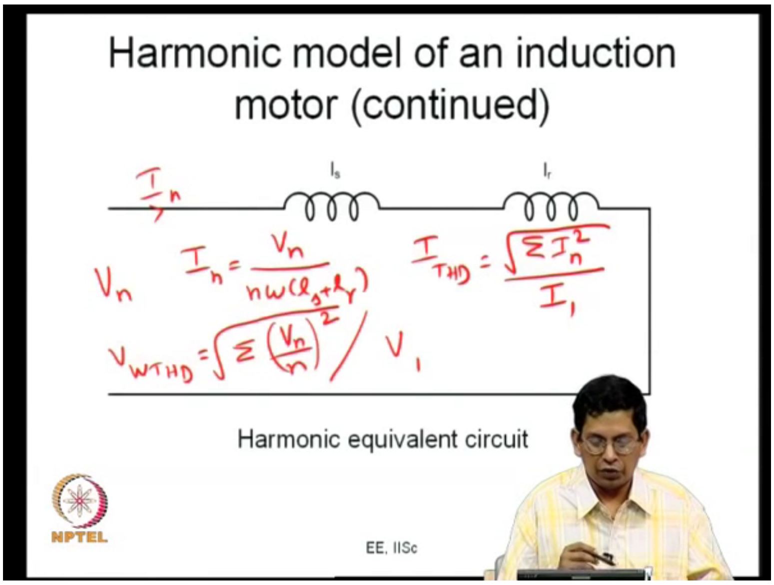

And therefore, the effective combination can be written like this it is l s and l r this is the harmonic model of that now. So, whenever you apply certain harmonic voltage V n the harmonic voltage V n sees this harmonic voltage, sees the motor as a as its leakage inductance. So, this V n drive certain current I n and this I n is given by V n divided by n times omega l s plus l r, l s plus l r as the leakage inductance omega s is the fundamental angular frequency. So, if is 50 hertz it is 2 into point 50 100 pi radians per second and n is the harmonic order that is maybe you know it is the 100 and first harmonic or whatever 113th harmonic one so on so forth. So, that is the harmonic order now.

So, you see that when you have certain voltage amplitude V n, V n upon m omega l s by R this is this part is the fundamental reactance and multiplied by n is the harmonic reactance the harmonic reactance is proportional to the harmonic order and therefore, you know the nth harmonic component current is simply proportional to V n by n and that was the reason why we consider V n by n. So, this V n by n itself is a measure of the harmonic particular current now right.

So, now let us say this is a single harmonic current now what you need is you want the RMS value what you would call as I THD. So, let us say that you would go into I THD and what is this I THD? You have sigma of in squared that is you have the nth you have the harmonic currents you may have different harmonic orders, you make a sum of all of them under a square root that is the RMS current ripple and this RMS current ripple you can divided by the fundamental current and this is going to give you the what is called as the total harmonic distortion factor here.

So, let me make a few points this I 1 is the fundamental current and then you know this various with the load on the motor it is quite usual to measure this under the no load condition why, because until the no load condition is when I 1 is very small with load I 1 generally increases and the distortion factor improves. So, normally the worst case scenario is given by the no load I mean the on the no load condition of the motor corresponds to the worst case scenario we would normally make the measurement under the no load circumstances now.

So, now let us see how you get an idea of the weighted THD here as we can look at here before. So, this I n what you have is in is simply proportional to V n by n. So, I n is proportional to V n by n. So, you just do a square of V n by n and you do a sigma of that and the whole thing you take under root this you can see is proportional to the numerator part here there is and this you can divide by the fundamental voltage now. So, this is what is called as your weighted THD of the voltage waveform this is the weighted THD of the voltage waveform.

So, why you do we call it as weighted THD every harmonic component V n is being divided by n. So, that is the rate as being given. So, the weightage is corresponds to how much harmonic current it would be able to inject and therefore, this is called weighted total this is total harmonic distortion factor of the current waveform and that is equivalent to the weighted THD of the voltage waveform. In fact, if you multiply this factor by you know something like roughly what is equal to the low loaded inductance of the machine to the block rotor inductance of the machine you would be able to get the I THD from here right. So, this weighted THD is the measure of the I THD and that was the reason I listed it as one of the features from a waveform.

So, once we have a spectral component these components can be directly seen, but this particular company requires a lot more calculation and that basically gives you what is your weighted THD or it is what it is a measure of the harmonic distortion factor that you will really have here. So, that is because of you know this model here.

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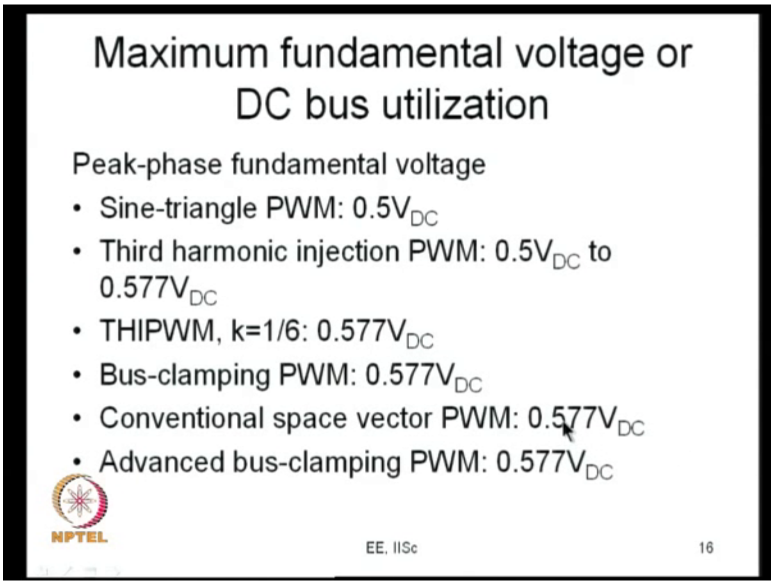

So, one of the things that we had there was the fundamental component that is the most important thing. So, we have to look at how big is the fundamental component now. So, you cannot produce whatever you want to, so there is certain maximum fundamental voltage as I mentioned earlier that is possible now right. So, the maximum fundamental voltage would correspond to the square wave operations really speaking, but with all the PWM methods there are some limits, if you do not want to go into over moderation there is some limit now.

So, this is sometimes called DC bus utilization because for a particular DC bus voltage how much AC voltage you can generate is a question. So, you call it DC bus utilization right. So, now, you see what is the peak phase fundamental voltage what I mean by that there is line side voltage and the line side voltage has the fundamental as well as harmonic components I am considering only the harmonic component and I am considering the phase to neutral voltage that is there is a load R Y B with the neutral n. I am considering the load to neutral voltage rn that is what I am considering the fundamental component of rn right and I am considering the peak value of the fundamental component of V rm that is the meaning of peak face fundamental voltage right.

Either you sine triangular PWM what happens is the peak phase fundamental voltage is 50 percent of V DC that is what you get right. Then the third harmonic injection you are able to push it a little higher that is anywhere between 0.5 V DC to 0.577 V DC depending on what is the third harmonic component you really had. And if that particular third harmonic component is equal to k is equal to 1 by 6 meaning k is the ratio of the amplitude of the third harmonic to the amplitude of fundamental. So, the third harmonic injected is one-sixth of the fundamental then you get 0.577 V DC this is the third harmonic injection that you get now. So, this is you get something like a 15 percent increase over that.

So, the same thing can also be achieved by bus clamping PWM and you can push your DC bus utilization to 0.577 V DC I mean you can push your peak phase fundamental voltage to 0.577 V DC. And if you go a conventional space vector PWM also the maximum peak phase fundamental voltage is 0.577 V DC and if you looked at advanced bus clamping PWM also it is 0.577 V DC.

So, that is what is the kind of the theoretical maximum that you can get this 0.577 V DC is the maximum value of the peak phase fundamental voltage that you can achieve with the DC bus voltage of V DC without resorting to poor modulation without introducing low frequency components in your output voltages.

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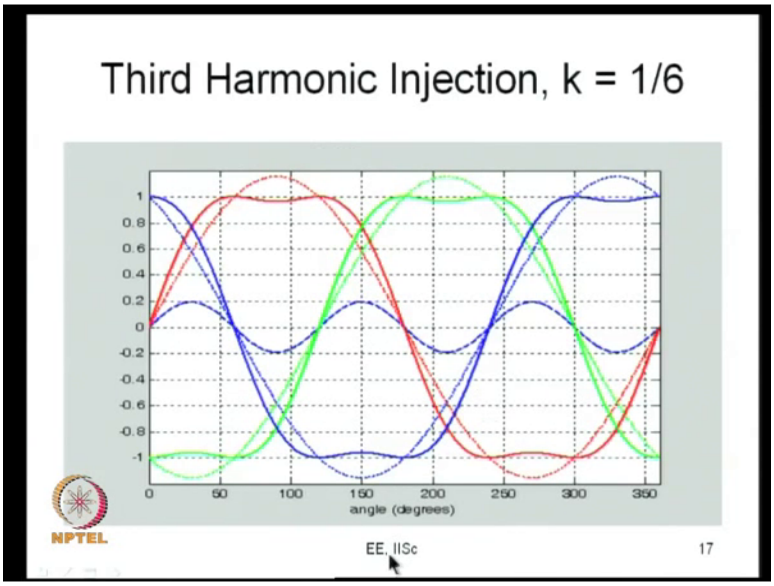

So, let us take a quick relook at this, this is at k is equal to 1 by 6 I have shown a peak signal of you know this is a sine signal which is off amplitude of 1.15 that is something like 2 upon root 3 and if you have these three-phase sine as I shown by the red yellow blue signals here we generate a common mode this is the third harmonic common mode when you add the third harmonic common mode what happens when this goes beyond the peak of that the common mode is negative and therefore, the common mode brings it lower than the peak value and you can see that this is how it is now.

And the peak value of the modulating signal though the peak value of the original sine wave is greater than that of the peak of the carrier the peak value of the new modulating signal is less or just equal to the peak of the carrier now and this is what makes you, you know it is something like you are packing a higher amount of fundamental voltage without exceeding the speak voltage now and you compare this kind of a waveform with the third harmonic you know the triangular carrier you are going to produce third harmonic injection and you can go up to 1.15. So, this is just trying to show the story, but that point that it is to reemphasize that this is 1.15.

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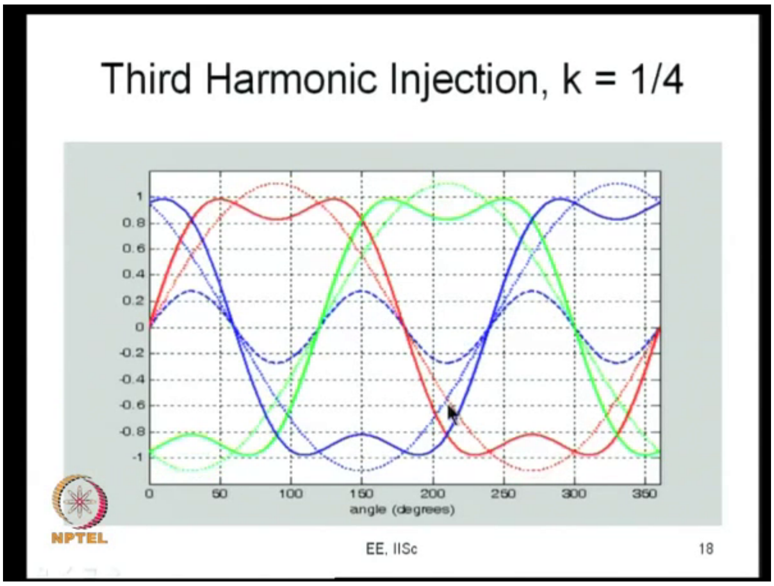

Similarly, this if it is k is equal to 1 by 4 you can see that I have taken something lower than that here it is something like its 1.15 to the root 3 whereas, here the peak I am taking is something like only 1.1. Even with that 1.1 you see that the peak of that is very close to that if I go to 1.15 you can very easily see that this peak will go above one. So, with k is equal to 1 therefore, it is certainly lower than 0.577 V DC.

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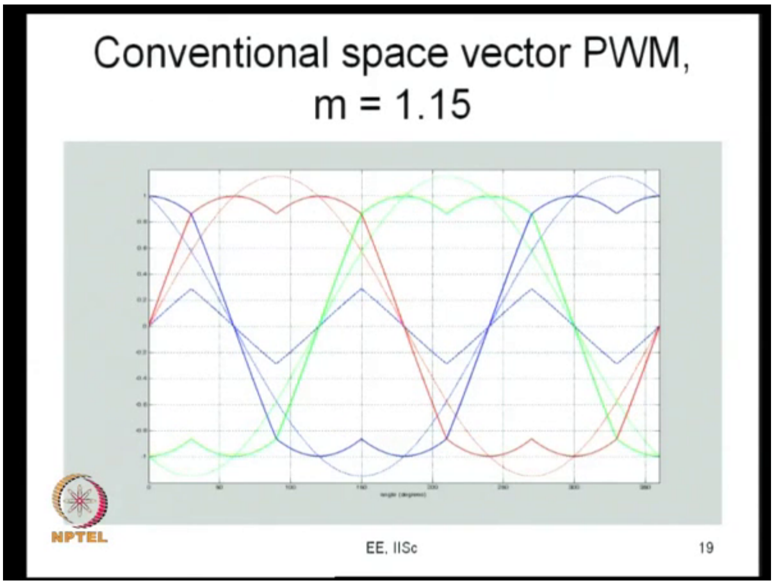

So, as I have also mentioned before as the k is equal to 1 by 6 we can go to 0.577 V DC. And if you go to conventional space vector PWM. So, the third harmonic component there is triple frequency component is. So, this is the sinusoidal component.

So, there are three-phase sine waves there is a middle valued wave you take 50 percent of the middle valued wave this is your common mode component which looks roughly like a triangular wave. This looks like a triangular wave because what you are doing here is here this is 50 percent of the R phase wave and R phase wave name is going through 0 crossing.

So, close to 0 crossing assignee looks almost like a straight line. So, this also looks like a straight line as I mentioned before and therefore, you go about adding this kind of a common mode component and the resulting modulating signal is what you get here and I have plotted this modulating signal for m is equal to 1.15 or which is very close to 2 by root 3 and you can see that the peak value of the modulating wave is almost equal to plus 1 minus 1. So, this is what you can get 1.15 instead of 1 or 1.1547 to be precise instead of 1. So, you have 15 percent higher voltage then sine triangle PWM.

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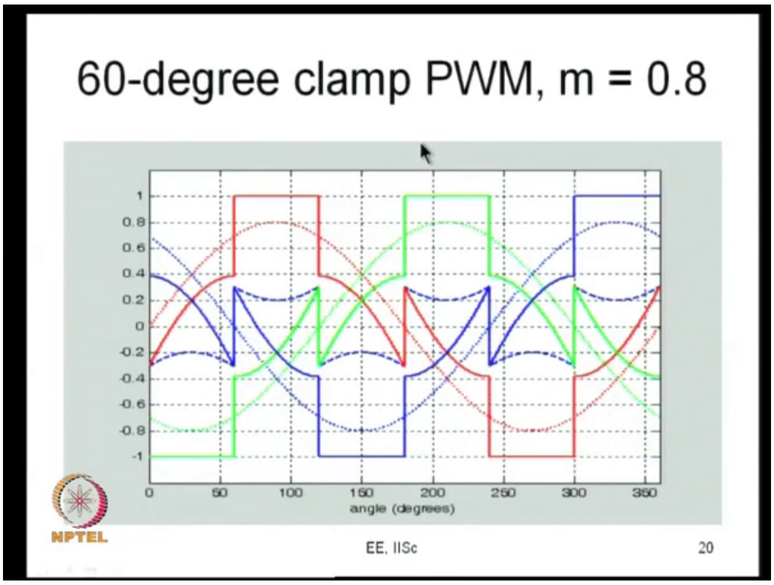

The same way with 60 degree clamp PWM when you want to clamp the middle 60 degree duration, so what you are doing is you are adding a common mode signal as shown by this blue dashed line and the resultant modulating signal is something like what you have shown here right.

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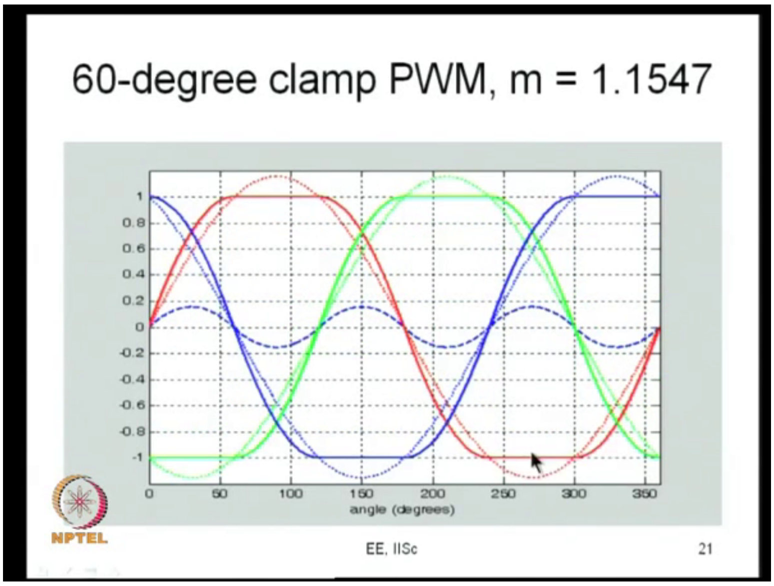

So, I have plotted the same thing for 1.1547 that is 2 by root 3 and you can see that this like here. So, I want to make the point that you really cannot exceed 1.1547 now.

So, if you look at it here you can see that this common mode component in this region is positive as m goes on increasing now we have looked at m is equal to 0.8 that is the ratio of the peak off sign to the peak of carried this 0.8 you go about increasing the ratio here to 0.85 0.9 etcetera this value will come down lower and lower and if it just touches 1 this value will be 0 here and when it crosses 1 what happens is this becomes negative and that is what is illustrated here. In this case you can see that between 60 to 120 degrees.

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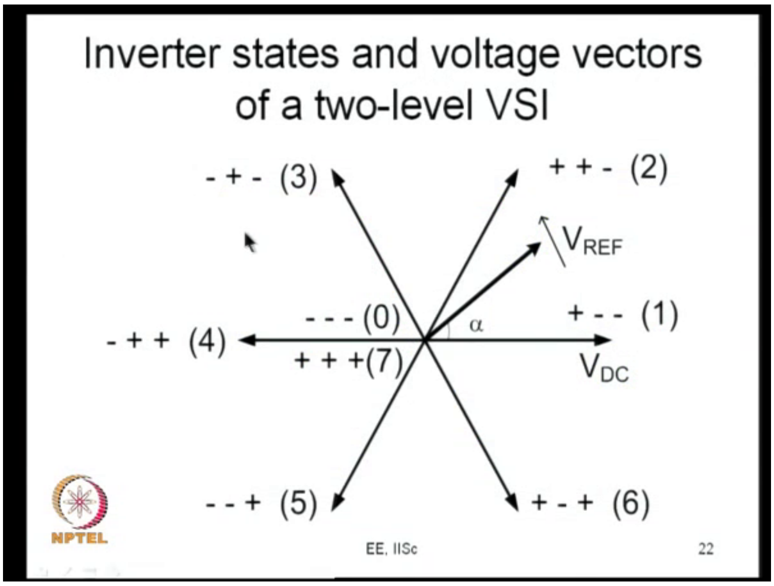

This is m equals I m sorry m is equal to 2 by root 3. So, sine 60 is root 3 by 2 times v peak right therefore, if the value here is 1, this peak is 2 by root 3 this is 2 by root 3 times sine 60 that is 2 by root 3 multiplied by root 3 by 2 therefore, this is 1.

So, this sine waveform it go crosses 1 at 60 degree and again you know comes below 1 at 120 degree between 60 and 120 degree it is higher than that. So, in this entire region the waveform is greater than the peak and the corresponding modulating signal is less than this now. So, if you add this kind of a modulating signal you can see that this waveform is equal to the peak at you know for 60 degrees exactly.

Now, let us say you increase it a little higher from 1.15 you make it to 1.2 what will happen? Here right now there is only 1 phase which is higher than 1 at any instant of time. So, in this initial instant this phase which is the yellow phase goes beyond minus 1, the next 60 degree duration the red phase goes beyond plus 1 and the next 60 degree duration the B phase goes beyond minus 1 on the next 60 degree duration the yellow phase goes beyond plus 1.

Now, if you go above 1.1547 let us say you consider something like 1.2 what will happen is you will have a situation where the red phase goes positive and also simultaneously the yellow phase will be negative and its beyond this minus 1. So, you have plus 1 and here it is beyond minus 1. So, if we have to bring this within the plus 1 you have to add a negative common mode signal if you add a negative common mode signal this fellow is already outside minus 1 and, they you may not get that. So, you will this will go beyond minus 1.

That is one of the constraints is by adding this common mode signal you must produce some m R star, m Y star and m B start which are within plus 1 and minus 1 which correspond to the positive and the negative peak of that that will not be possible if you exceed m is equal to 2 by root 3.

I am showing this just with the illustration of 60 degree clamp PWM and that is true for many of them. So, this m is equal to 2 by root 3 is the absolute limit up to which you can maintain this linearity I mean you can produce PWM waveforms without getting into over modulation if you go into ms equal to 1.2 or 1.3 what is going happen is you will have a distorted waveform m R star my star would go outside plus 1 or minus 1 that basically means that there is clamping and you will see that the resulting it is not only third harmonic component you will also get other components injected into that we will discuss this subject in our one of our last modules in later modules which you would call as I mean over modulation and discuss this problem.

When you do not want to go into over modulation m is equal to 2 by root 3 is a limit which I would like to reemphasize it is not only for 60 degree clamp its true for other kinds of PWM methods also. So, I would, I will just stop at that and look at the same thing from the space vector point of view. So, if you look at the space vector point of view instead of three-phase sine waves you are going to have a rotating vector which we call as V REF and in this case you know it falls within the so called sector 1 and so we will use this vector 1 and vector 2 and the null vector to synthesize this vector over a sub cycle like what we have said this.

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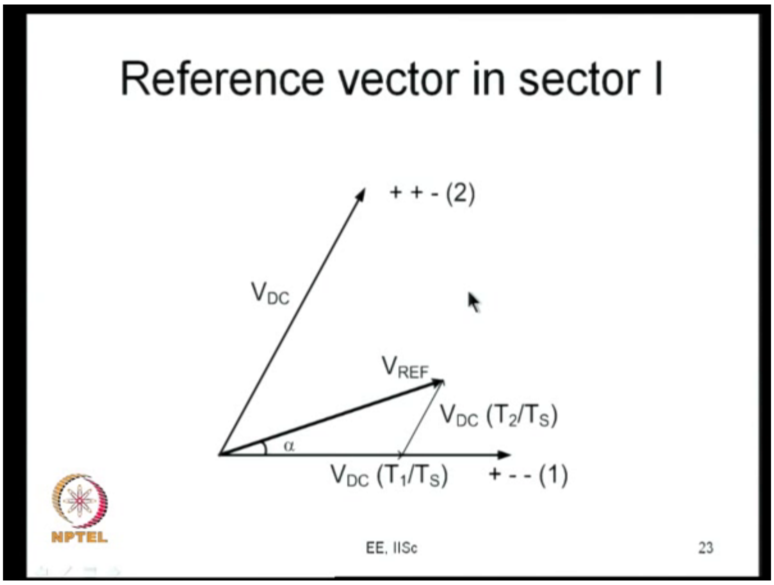

We will apply the vector 1 for some duration T 1 seconds vector 2 for some durations T 2 seconds such that V DC times T 1 by T as in V DC times T 2 by T S simply add up to the required V REF and T 1 plus T 2 is less than the total sub cycle time and the remaining time for you know that is T S minus T 1 minus T 2 for that time we will apply the null vector which is here right.

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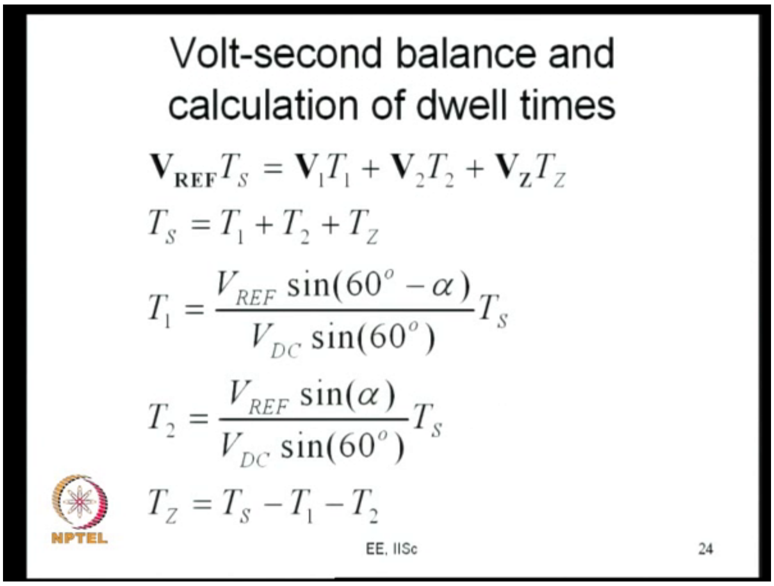

So, this is what we do and this is how the calculations are exactly done, were ref T S that is the volt second is equal to this side is the applied volt second. So, V 1 T 1 plus V 2 T 2 plus V Z T Z and the calculations are done like this as I showed in previous classes now.

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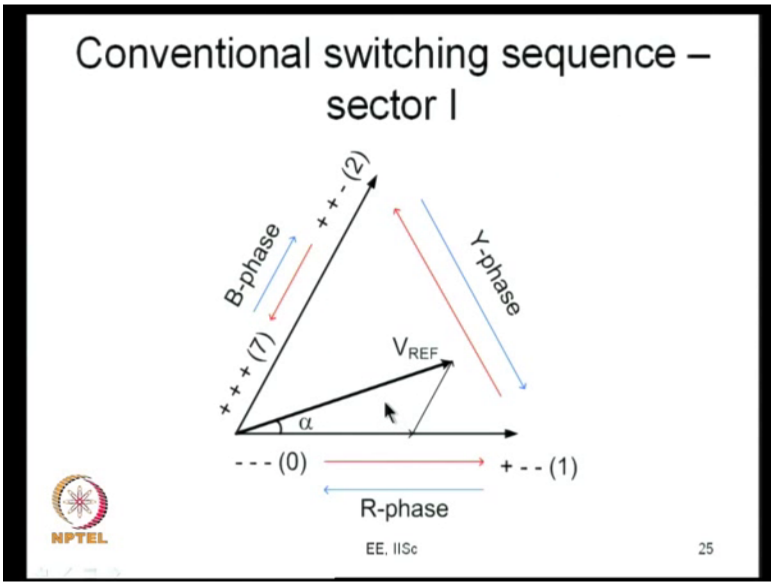

So, you do all this and you look at the switching sequence the calculations are you know we here you calculate T 1 T 2 and T Z and in conventional space vector PWM you use both the 0 states. So, you upload this for it is it by 2 seconds then go here T 1 seconds go here at T 2 seconds and go here for T Z by 2 seconds and then you come back. So, this is what you do in conventional.

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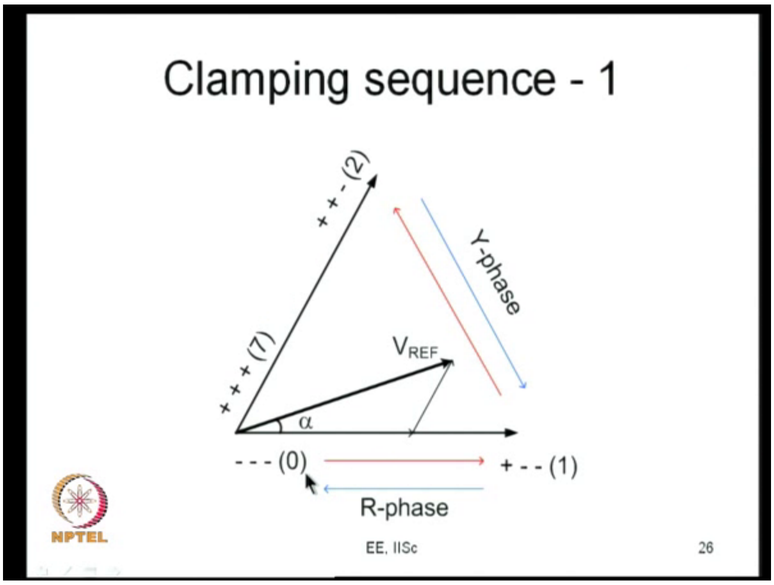

In case of clamping what you can do is you can skip 1 of the 0 state for example, plus plus plus you start from minus minus minus apply this for T Z seconds apply this for T 1 apply this for T 2 and back. So, this is clamping, one kind of clamping where you see that the B phase does not switch at all and the B phase is always clamped to the negative bus here it is minus minus minus it is negative, here plus minus minus B phase is negative here plus plus minus is also B phase negative. So, if you do like this B phases clamp to the negative bus.

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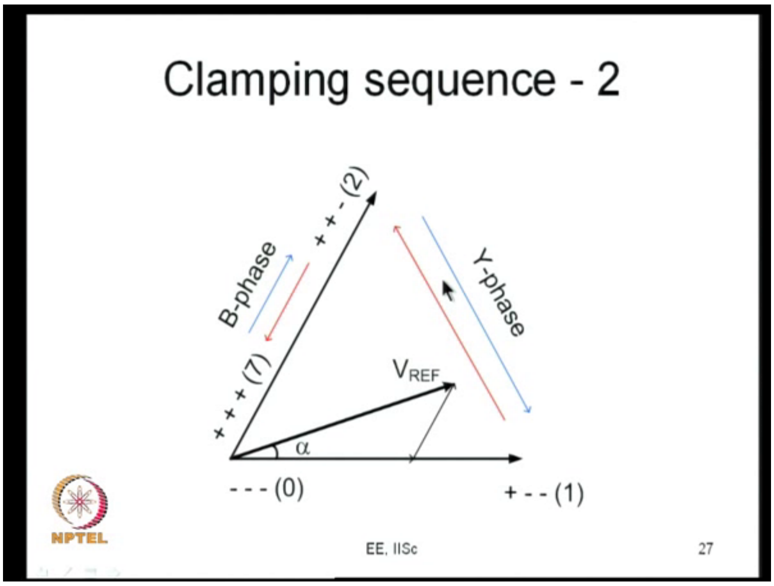

Now, you know alternatively this is skip minus minus minus and so you can use this plus plus plus can be applied for T Z seconds this for T 2 seconds and this for T 1 seconds if you do that you can see B and Y are switching, but R phase is not switching now.

In this case you can see R phase is positive here, positive here and also positive here.

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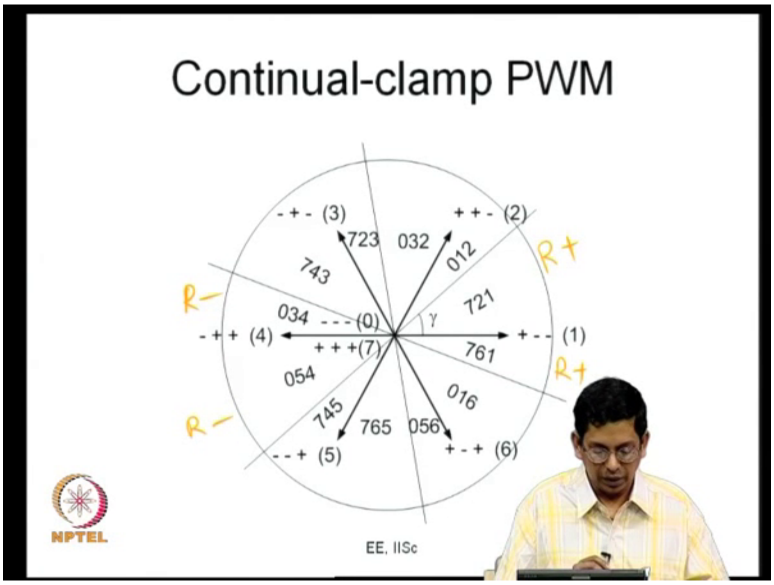

So, in this case I m sorry the R phases always clamped to the positive bus. So, you have a situation of B phase getting clamped to the negative bus or R phase clamping to the positive bus whenever your reference vector is in sector one. So, there are 2 different kinds of clamping now. So, you can use the sequence 012 or 7 to 1 to realize your vector in the vector 1.

So, there are only 2 options either you 7 to 1 in some initial portion the 60 degree you know we cannot do the same 0 state we have to change it once in every 60 degrees as I mentioned during my previous lectures on the bus clamping. So, for certain gamma we can apply 7 to 1 and after that we can apply 012. On the other hand we can also dos 0 1 to the certain gamma and then apply 721, in this gamma itself can vary anywhere between 0 and 120, 0 and 60 degrees now.

So, in this case if you looking at 7 to 1 as I mentioned before R is clamped to the positive bus here and here also always clamp to the negative bus. Again if you do an analysis here you will find that R is clamped to the negative bus here and here also R is clamped to the negative bus. So, this is corresponds to a situation where you have the R phase clamped continuously for 60 degree durations there is this continuously clamp for a 60 degree duration and if gamma is equal to 30 the 60 degree duration is positioned at the middle of the positive half carrier cycle of the positive fundamental cycle. Otherwise yow now with change in gamma and the 60 degree position kind of changes goes to the left or to the right the same way it is with R minus like this. So, you have this now.

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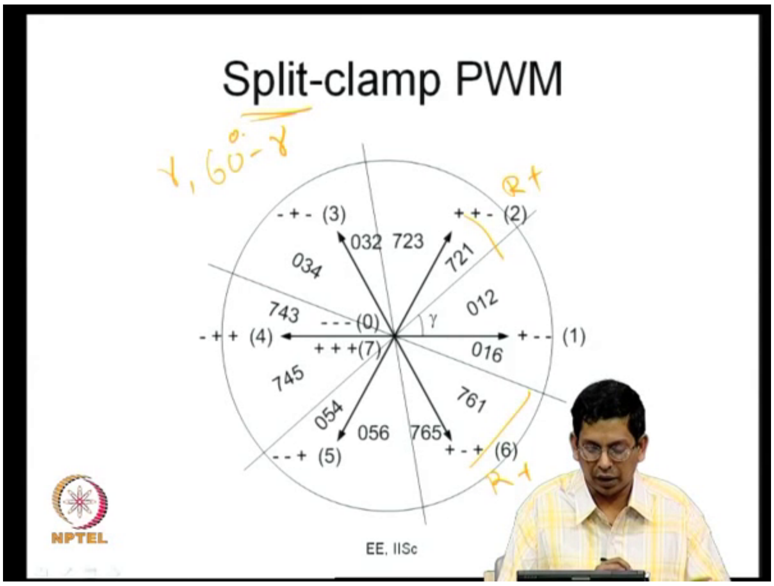

Instead if you go to split clamp PWM as I mentioned before you have the situation where R phases clamp to the positive bus here and R phases clamped to the positive bus in this case. So, these are the durations now. Now you can see that durations are unequal and this duration is gamma and this duration 60 minus gamma they add up to 60 degree. So, the 60 degree continual clamp was split into 2 parts one of gamma and the other one equal to 60 minus gamma and that is what is split clamp PWM.

So, the bus clamping can be classified into continual clamp and split clamp PWM when you this is very very easy when you look at it from the space vector point of view right. So, you can say that it is either 012 if you are in sector 1 you use either 012 or 721 let us say you are 7 to 1 in the first portion of sector 1 and go to 012. So, that leads to continual clamping or the other alternative use 012 first and then 721 next and that leads to split clamping PWM. So, bus clamping PWM if you look at it this way it is very very easy to just split it into a continual camp and split clamp and a special case of split clamp is 30 degree clamp and the special case of continuing clamp of 60 degree clamp right.

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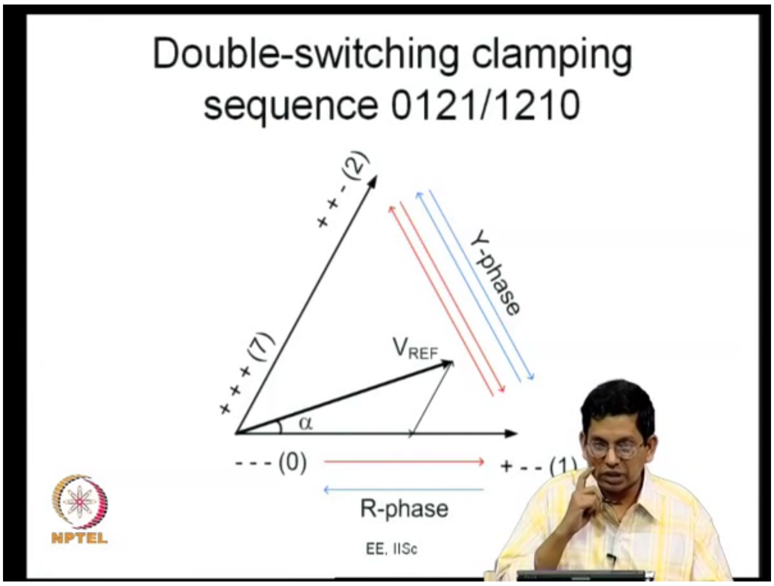

So, this is the double switching sequence I said which cannot be done actually using the I am I mean triangle comparison approach why, because in triangle comparison approach you are comparing the three-phase sinusoidal signals which are samples of three-phase sinusoidal with only one rising carrier or falling carrier there is only one intersection, only one switching. Here you find R phase which is once and Y phase which is twice that is not possible with that.

It is similar to the bus clamping PWM in the sense that one is not switching for example, B phase is not switching and you can see that B is always negative is negative here, is negative here, is negative here. So, in the entire sub cycle B phase negative, this is similar to the bus clamping, but you see that Y phase double switches and that is why you call it double switching clamping sequence there is one variety of double switching clamping sequences I mentioned in previous classes now.

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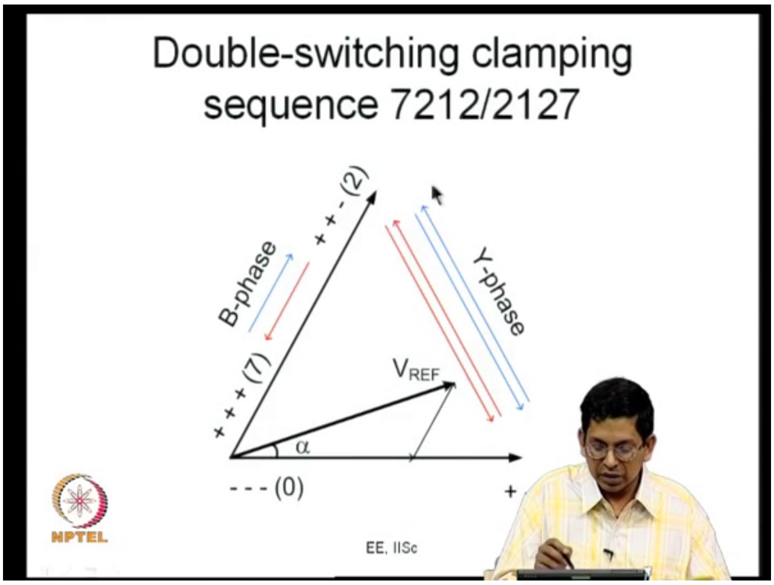

And this is another variety of double switching clamping sequence the 7212 and so you can do is start from 721 and 2 now you go about doing this now.

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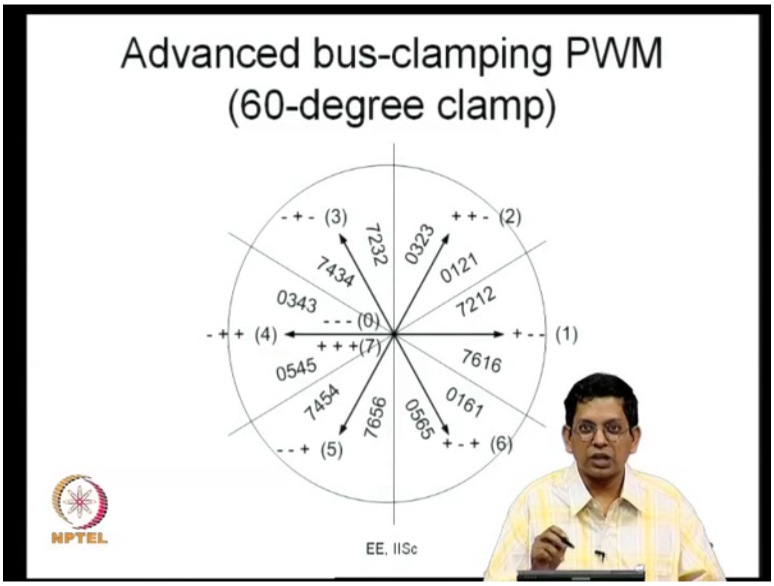

We are now I mean I am taking a quick review of this we are no basically focused and finding out what is going to be the you know DC bus utilization. So, you know going to you know bus clamping to advance bus clamping what you can do is in the so called continual clamp you can replace the 7 to 12 by 0 721 by 7212 or 012 by 0121 and this gives you advanced bus clamping a 60 degree clamp PWM. So, if we generalized that that becomes 30 degree.

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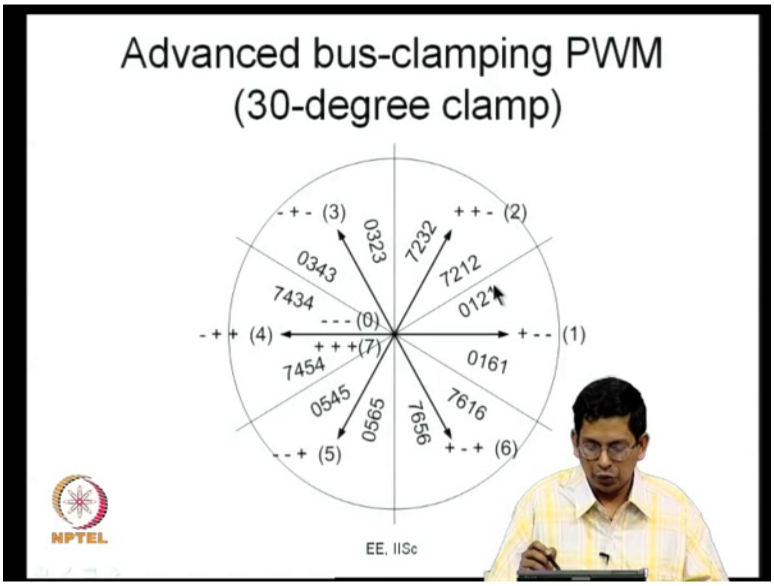

So, this is again instead of 0 1 point the bus clamping use 0121.

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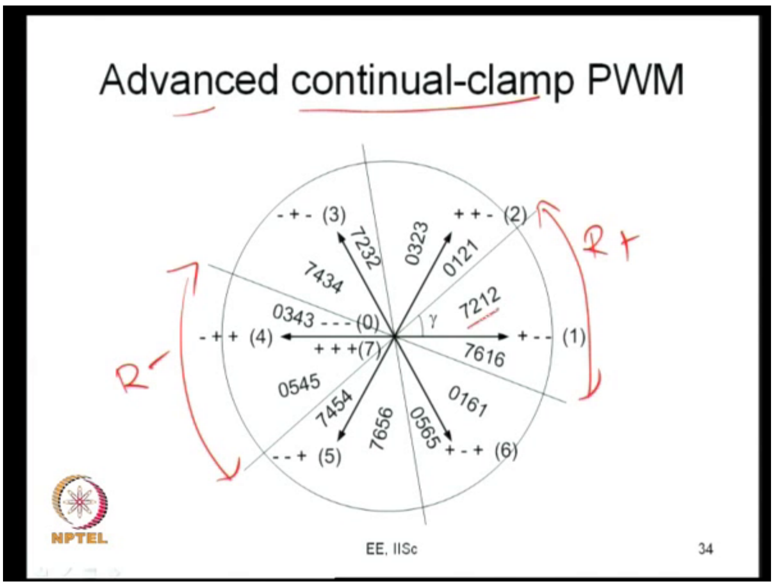

And 7 2 instead and you know 7212 instead of 721. So, you know this is my advanced continual clamp. So, instead of 7 to 1 I am using 7212 and instead of 012 I am using 0121. So, I have advance continual clamp and we also have advance split clamp. So, you can use 0121 in the first portion of sector 1 and 7212 in the second portion of sector 2.

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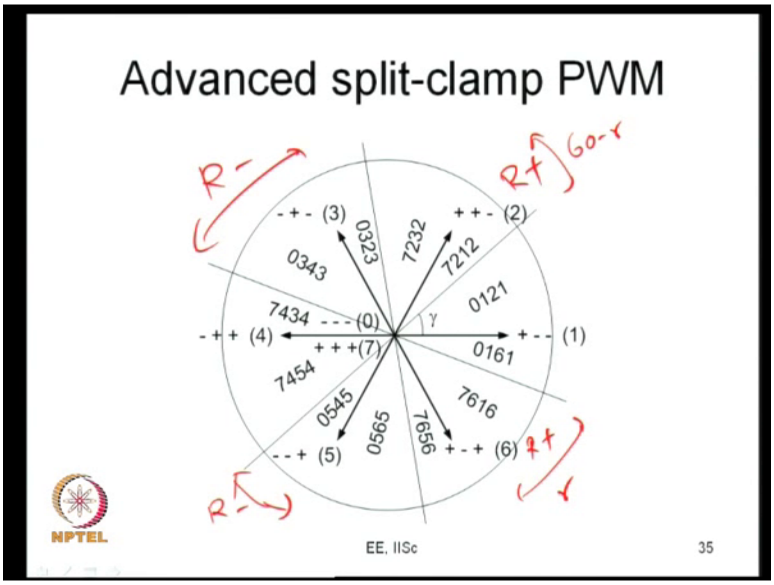

So, let us just look at how the R phase would be the R phases is clamped here to our plus here also it is R plus this is for a duration gamma and this is for a duration 60 minus gamma. The same way you will find R phases clamp in this portions also, but to the negative phase you will find them clamped in these regions also this will be R clamp to the negative bus.

So, this is advance split clamp its similar to split clamp, but the difference is one of the phases always switches at twice the nominal frequency right. And this is continual clamp because here you will see that R phases clamp to the positive bus continually for 60 degrees and here you will see that R phases clamped to the negative bus continually for 60 degrees now.

So, you can extend the ideas of continual clamp to advanced continual clamp by using these sequences 7212 0121. Similarly you can extend the ideas split clamp to advance split clamp by utilizing the sequences 0121 and 7212, so this is what we are doing now. In all these cases we are you know we are handling the problem in the space vector domain.

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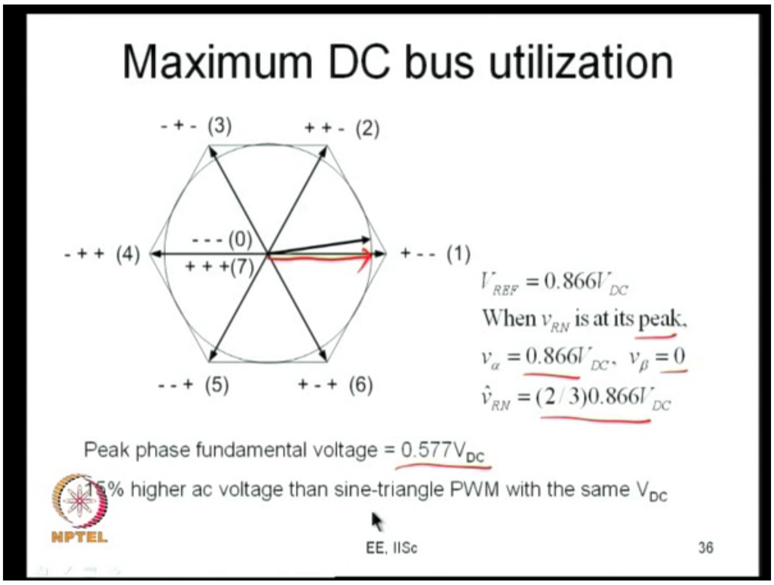

So, in the space vector domain you have the 6 vectors like this you have the 6 vectors like this and this active vector 1 2 3 4 5 6 and you can join them using a hexagon now.

So, you have this V reference vector and the V reference vector should have the same magnitude in sub cycle after subsequent over the entire cycle. So, that is the case the highest value it can take is equal to the radius of the inscribed circle this corresponds to the highest value of reference vector magnitude and that is V REF is equal to 0.866 V DC that is the side of this hexagon is V DC and its cause 30 degrees 0.866 V DC is the highest value of V REF.

Now when V REF is 0.866 let us say V REF is itself is rotating let us consider a particular instant where V RN is at its peak that is when V RN is at its peak the reference vector will be here will be aligned here like this will be like this. So, let me draw it here for your benefit. So, at that instant it will be like here this is where your v reference vector will be when V RN is at its peak now and resistance instance you can see that your v alpha is 0.866 V DC and what is the v beta is equal to 0. So, you can use the space vector transformation v alpha is equal to 3 by 2 times V RN and therefore, V RN peak is simply equal to 2 by 3 times 0.866 V DC and what is 2 by 3 times 0.866 that is 0.577 V DC.

So, this is a proof from the space vector point of view why as to why peak space fundamental voltage is equal to 0.577 V DC. I mentioned this very quickly in one of the previous lectures here I have taken the time to is go through some more steps. So, you can look at it either from the triangle comparison point of view or space vector point of view you will find that conventional space vector PWM third harmonic injection with one-third and bus clamping PWM all would give you a maximum value of 0.577 V DC for the peak phase fundamental voltage when any space vector by PWM would give you something like 0.577 V DC.

So, this is what you get now. So, when you go to something like advanced bus clamping PWM you have the advantage of space vector PWM of conventional space vector PWM of namely of this increased AC voltage. In addition to that there are certain advantages in some, under certain operating conditions like in terms of line current ripple as we would see probably you know in a little while or and also in the next lecture now.

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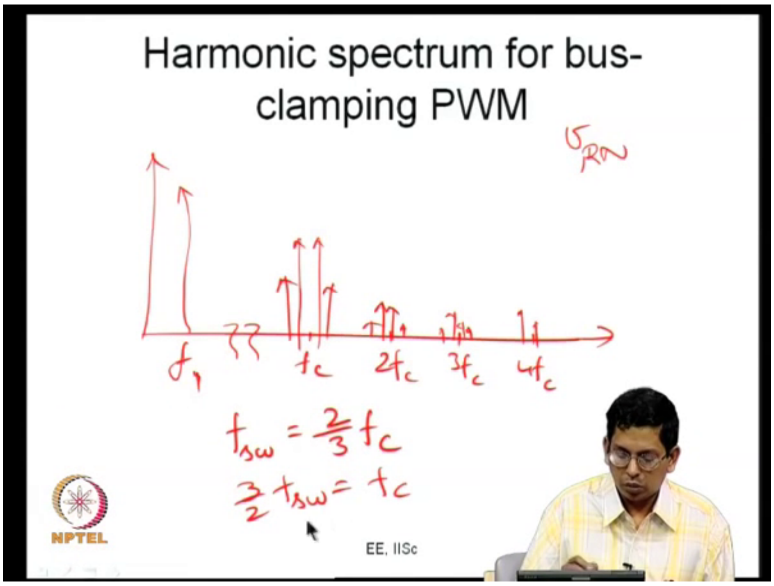

So, you have this now. So, we looked at the harmonic spectrum of sine triangle PWM earlier if you look at the harmonic spectrum for example, of the bus camping PWM this structure is kind of going to be very very similar. So, you have the output voltage we are considering the output voltage V RN that is R is the load terminal N as the load neutral we considering that voltage and if you look at the components as before you will have the fundamental frequency component f 1, I m sorry this is the fundamental frequency component f 1 now and you will have a large break. And there is carrier frequency f c there is 2 f c, there is 3 f c, there is 4 f c and around this you will have harmonic components as before you will have harmonic components as before yes before.

So, this is the nature of the harmonic spectrum for bus clamping PWM in general and you see from PWM method to PWM method this will change. It is sine triangle PWM you will get something and if you add third harmonic injection the harmonic components will change. Let us say in bus camping PWM if you look at 60 degree clamp PWM and if you look at 30 degree clamp PWM for the same fundamental amplitude you will find that there are some small differences in this harmonic amplitudes and that is what causes certain difference in the line current ripple. We will not go into what would be the amplitude with 60 degree clamp and what would be the amplitude in 30 degree clamp rather we would try and understand how the RMS line current ripple will be different in these 2 methods in our methods of analysis.

So, now, right now this is what I will say that this is f c, 2 f c and 3 f c you have the first harmonic sideband and the second harmonic sideband, third harmonic sideband and the 4th harmonic sideband right when we looked at the similar thing for carrier in the sine triangle PWM where f c itself was equal to the switching frequency. Now in this case this is equal to 2 thirds of switching frequency this is equal to two-thirds I am sorry it is 3 by 2 times the switching frequency that is if you switch it f c right this is the carrier frequency is always not switching.

That is what is my switching frequency, my switching frequency f sw is 2 by 3 times the carrier frequency or carrier frequency is equal to 3 by 2 times f sw. So, what you have is this is f c or 3 by 2 times switching frequency. So, what you can do is when you go for third harmonic I mean when you go for bus clamping PWM what happens is your effect of switching frequency reduces to two-thirds on the carrier frequency that can give you some benefit in terms of reducing the switching loss, but your harmonic amplitudes can increase actually speaking.

On the other hand what you can also do is you can maintain the same switching frequency how can you maintain this main switching frequency by increasing the carrier frequency by 1.5 times, you can increase the carrier frequency by 1.5 times to maintain the same switching frequency as sine triangle PWM or conventional space vector PWM. If you do that what happens this whole thing gets shifted by 1.5 times. So, when the whole thing gets shifted to the right by 1.5 times what happens is the harmonic reactance are seen by these components are increased.

So, one advantage with bus clamping PWM as I mentioned before is the reduction in the switching frequency you can make use of that advantage and that would reduce your switching loss and the heating of the inverter. On the other than what you can also do is you can maintain the switching frequency is same as seen though sine triangle PWM and therefore, you can increase the carrier frequency to 1.5 times, if you are increasing the carrier frequency by 1.5 times let us say we are considering 5 kilohertz switching frequency this becomes 7.5 kilohertz instead of 5 this becomes 15 kilohertz instead of 10.

So, the sidebands get shifted by 1.5 times and the reactance is seen by them increases by 1.5 times and that is going to reduce the harmonic currents driven by these components now. Therefore, this bus clamping PWM methods have an advantage in terms of line current ripple particularly at high modulation indices at high modulation indices when we have the same switching frequency when we increase the carrier frequency by 1.5 times, so that something that I would like to mention here now.

The same way if you look at the advance bus clamping PWM the basic structure would look similar; the basic structure would look similar.

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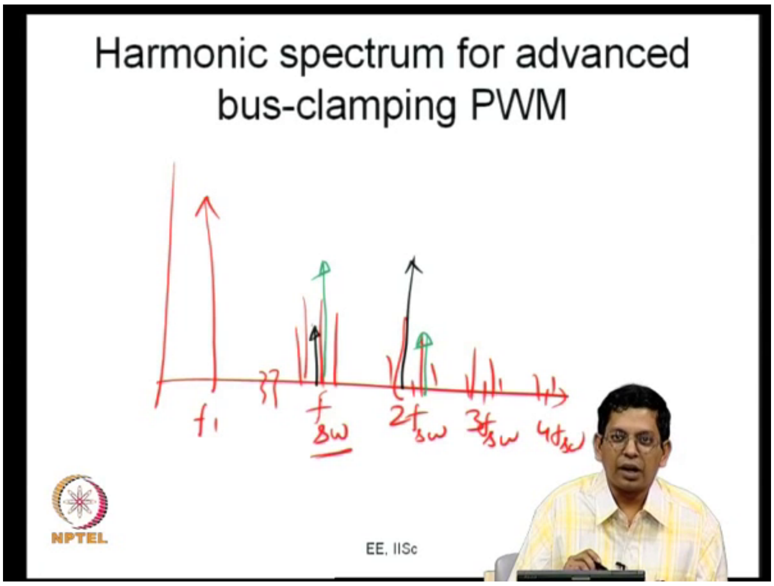

So, you have the amplitude versus frequency you will have the fundamental component and there is a large separation. So, here we cannot talk of carrier frequency we would talk in terms of the switching frequency this is the average switching frequency. What is the average switching frequency? It is the switching frequency averaged or a line cycles sometimes phase which is at nominal frequency, sometimes at double the nominal frequency in, sometimes it is clamped and the switching frequency is the average value of the switching frequency over a line cycle. We have f sw, you have 2 f sw, you have 3 f sw and so on and 4 f sw and so on and you will once again have harmonic components around this you will have harmonic components around this. This is how the nature is going to be.

So, these all these methods will actually differ you know for a same fundamental voltage you will find that the harmonic components are different. So, we have to just understand that how different they are sometimes they may be different for better sometimes they might be different for worst. So, for certain modulation indices mean for some magnitude of the fundamental voltage let us say conventional space vector PWM will be better than some other PWM sometimes vice versa.

If you take a high modulation index what you will find is advanced bus clamping PWM will be better I will tell you how. So, what happens is now I have shown a case where the first sideband is a little more than the second sideband now. So, what happens in the case of at very high modulation indices is the second sideband becomes dominant then the first sideband. So, let me just draw something in a different color.

So, for example, you may have the second sideband like this, but the first sideband may be like this. So, the second sideband is dominant when the second sideband is dominant the second sidebands is much lower current it sees you know, it sees a double their leakage reactance and therefore, the corresponding current is low this happens at high modulation indice. So, at high modulation indices the advanced bus clamping PWM results in lower one than conventional PWM, if you look at the conventional case I will show you in a different color let us say green color in conventional what you will find is you will find the dominant component something like this and the second dominant the sideband compared something like this as I have indicated. See these are all indicative just to get some feel for the problem.

So, in conventional you have the first two component at some high values of modulation index you get the first component is dominant and the second component is not so dominant. So, the corresponding current you know this dominates the leakage reactance in by this component is not very high therefore, there is some RMS current ripple. Whereas, in the advanced bus clamping PWM the second sideband is dominant and second sidebands is double the leakage reactance than the first sideband harmonic therefore, the current ripple produced by this is lower therefore, advanced bus clamping PWM you will find these advantageous usually at very high modulation indices and so this has been given in some reference.

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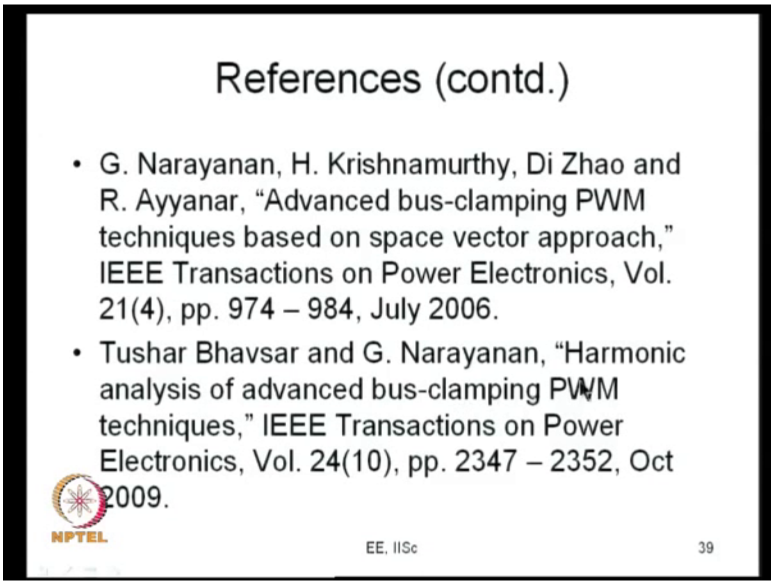

So, this particular reference particularly you know this was mentioned in this advance bus clamping PWM techniques paper this has been indicated now. In this paper this paper Tushar, Bhavsar and Narayanan there has been a more you know exhaustive comparison of conventional space vector PWM and the advanced bus clamping PWM methods. The dominant component in the first sideband and the dominant component in the second sideband have been compared over the range of modulation indices I will. So, you for a detailed you know quantitative study of this you can really look at this paper and get an idea how the different PWM methods are different how their spectral components vary with modulation index now.

So, with this I end this lecture. So, we have been trying to basically look at this PWM methods and you know we had a relook at the PWM methods triangle comparison the space vector ones and we would try to say how much is the DC bus utilization and we have been trying to look at the harmonic spectrum. Now in the harmonic spectrum we have the fundamental component then we have a switching frequency components now. For the same fundamental component different harmonics will give you a slightly different switching frequency components and that is what is the difference in terms of waveform quality between various PWM methods.

And what you would normally find is conventional space vector PWM is good at low modulation indices and even at medium modulation indices. At high modulation indices you will find that the discontinues PWM method or bus clamping PWM method will slightly improve and at very high modulation indices close to full modulation index advanced bus clamping PWM method it is what is very advantageous and that you can look at the reference I indicated to you. And I thank you for your interest in this and look forward to seeing you again in the next lecture.

Thank you very much.