Pulsewidth Modulation for Power Electronic Converters
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Lecture – 18
Triangle-comparison based PWM for three-phase inverter

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

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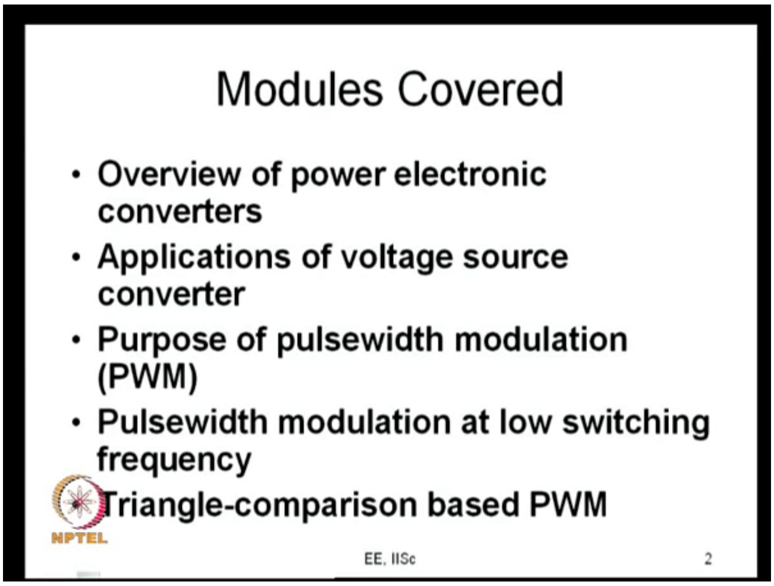

So, so far we have covered a few modules that just take a quick look at what are the various modules you have covered here. So, first we had an overview of power electronic converters. So, in this over view of power electronic converters we looked at various things like we started from switches and we looked at DC, DC converters like buck converter, boost converter, etcetera and finally, we came to voltage source converters and current source converters and covered multi level converters etcetera.

So, from here we picked up this voltage source converters I mean with particular emphasis we have been particular emphasizing on three-phase voltage source converters and we discuss various applications of voltage source converter like you know one application for example, is motor drive which is what we have been you know which is again a focus here area here. You can also look at active front end converters or power factor corrected compensated rectification and they are also using this voltage source converters they are also used for harmonic compensation and reactive current compensation etcetera.

So, we had an overview of various power electronic converters and we also looked at various voltage source I mean the applications of voltage source converters and these two topics I would say the first two topics they actually you know are actually more subject material of other courses you know we covered a part of this only to establish various good fundamentals over power electronic converters before we launched onto pulse width modulation. And in the subsequent module we launched onto pulse width modulation it is called as purpose of pulse width modulation why we do that.

Now, if you take a voltage source converter, the voltage source converter has a DC voltage on one side and it requires the ac voltage on the other side. So, the purpose of the pulse width modulation is to make sure that you can control the fundamental voltage that is one of the purpose of the fundament this thing and the other reason that you need to do is other than the fundamental voltage which you desire there are also harmonic voltages that get generated and these harmonic voltages have to be mitigated they have to reduce to some extent if not eliminated totally.

And this harmonic voltages also have certain adverse effects they like extra heating and pulsating torque and so on and so forth we will have to care try and mitigate those adverse effects of these harmonics and that is what we would call as purpose of pulse width modulation essentially two-fold, to control the fundamental voltage and to mitigate the harmonics and its bad effects.

And from that point we looked at pulse width modulation at low switching frequency we considered the situation when the voltage source inverter switches at a low frequency, now why. Firstly, actually this is very very relevant in you know you mean relevant a few decades back when the switches available the person mechanical device is available could not switch at very high frequencies they switched at rather low frequencies now like something like 400 500 hertz kind of frequencies now. But the modern devices switched at much higher frequencies nevertheless this is still relevant in certain contexts such as high power drives this low switching frequency is really what we mean here is the ratio of switching frequency to modulation frequency is low.

So, in high power drives you still have situations where the switching frequency could be very low because the power levels are very high and the device is really still con switched very high frequency. Further you have the other application which are high speed applications your switching frequency may be quite high it I mean may be like 10 to 15 kilohertz, but the modulation frequency itself could be something like 1.5 kilohertz, 1 kilo hertz, 1.5 kilo hertz are little higher than that. So, that happens in high speed drives and when such in such kind of cases the ratio of switching frequency the fundamental frequency is low and once again this becomes are relevant.

And what I would say is rather than the relevance of this to the present context this is more value to us from a learning point of view. It is very very important very useful step to go through this I mean to learn how to control fundamental voltage and how to handle the harmonics which are the two you know what you would call as the purposes of our objectives of pulse width modulation it is actually the low switching frequency gives us a very good opportunity to learn there and that is the reason why we went through that. We looked at a single switching angle with one switching angle we could control the fundamental voltage with two switching angles we learnt how exactly to handle the fundamental over how to maintain the fundamental voltage and also handle the harmonic voltages.

So, what we would like to say that this actually it is for us we did this exercise for us to realize that there are several options available. For example, you have voltage source inverter and you want to produce about 80 percent fundamental voltage now the fundamental voltage should be 80 percent of the square wave as fundamental voltage. Firstly, what we do as I mean as a result of that exercise we realize that there are several possibilities, there are several options are available for you to produce an 80 percent fundamental voltage, several sets of switching angles can give you that.

So, first there are several options and then what are those options and then how to evaluate those options. For example, if you want 80 percent fundamental voltage with only 2 switching angles you can look at eliminating fifth harmonic as own possibility or you can make sure that fifth and seventh harmonics both are low that is another possibility or you can try and make sure that be pulsating tark let us say the six harmonic pulsating tark is low.

Like this you can evaluate different options that are available and you can go in for this low switching frequency that was the reason why we went through the step of pulse width modulation at low switching frequency. And from this point we are going to what is currently more relevant which is the triangle comparison base PWM. You take a practical inverter. Now most of the inverters are likely to be switched with something like sine triangle PWM or some variant of sine triangle PWM and this is a very very common way of doing this and this is what we have been dealing with the over the last 3 lectures and today would be the concluding lecture of this particular module on triangle comparison based PWM.

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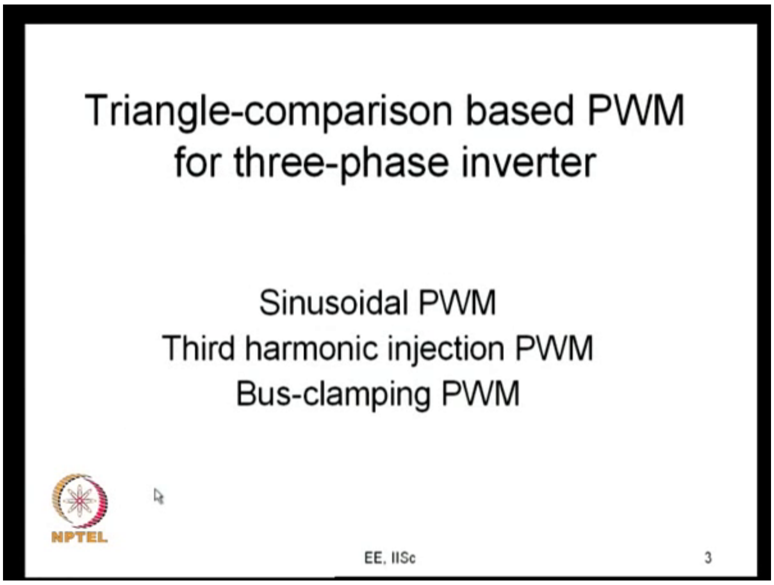

So, let us see a little more on what is this now. So, as part of this triangle comparison based PWM we have been looking at three-phase inverter, all that we saw earlier was we looked at sinusoidal PWM. We looked at sinusoidal PWM for both single phase as well as three-phase inverters and we also looked at third harmonic injection and bus clamping PWM. I can say that all this like sinusoidal PWM third harmonic injection bus clamping PWM are all specific cases of triangle comparison based PWM now. So, today we would just consolidate our understanding of this and try to generalize all this and get an consolidate our understanding on triangle comparison base PWM. So, this lecture is going to specifically focus on triangle comparison based pulse width modulation for three-phase inverter right.

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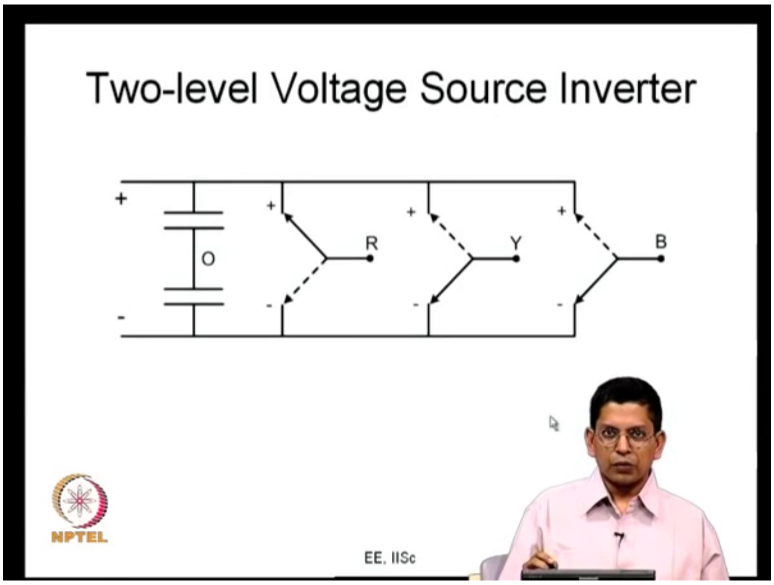

So, now what is a three-phase inverter it just a quick recap we know that there are 3 legs corresponding to every phase and each leg is a single pole double throw switch this is pole this can be connected either to the top throw or to the bottom throw similarly all these poles are there now. And a voltage source inverter this is how this is how you can draw that using generic switches, and if we were to realize with IGBTs this is how you can realize.

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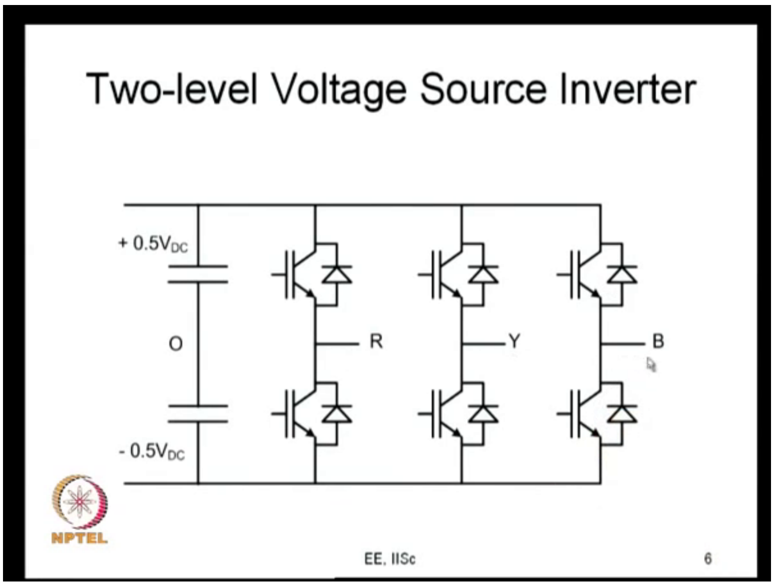

So, everything is a bio directional switch as we have talked about you know several times earlier in this course and these two switches the top and the bottom switch is in each leg switch in a complementary fashion now.

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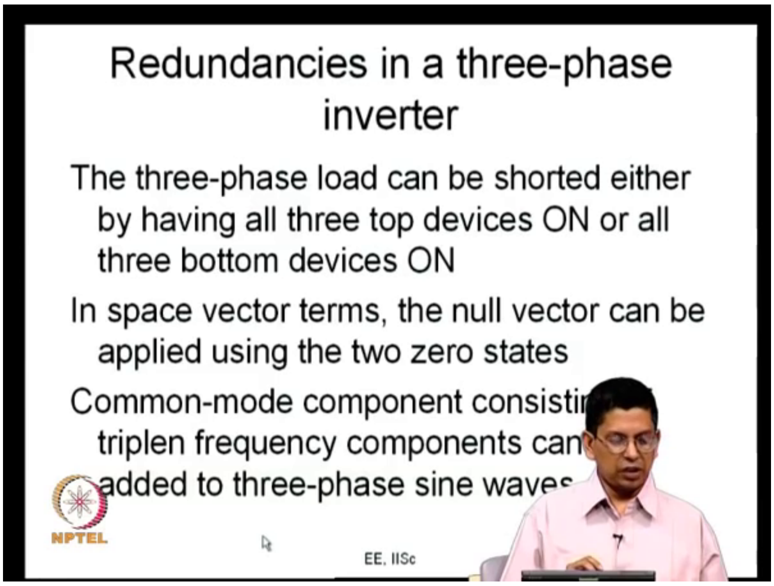

So, as we have mentioned before there are certain redundancies which are available in this voltage source inverter. So, what is that redundancy a three-phase load can be shorted either by having all 3 tab devices on or all the bottom devices on.

If you look at here now let us say all the top devices are ON it short R Y and B that load is getting shorted R keep all the top devices ON and all the bottom devices are I mean bottom devices can be ON with the top devices being OFF once again R Y and B are shorted. First the load can be shorted in two different ways either having all the top devices ON or all the bottom devices ON.

So, in space vector terms I am throwing a new term at you called space vector which we will be actually starting to deal with from the next lecture onwards, but you know I am taking the liberty of throwing this term at you a little prematurely. So, what is that? This is actually what do you mean by space vector is a transformation there is a transformation called space vector transformation which we will discuss in the next lecture and the space vector transformation transforms three-phase voltages into a 2 dimensional vector 2 dimensional voltage vector.

Now what exactly is this transformation we will discuss it in the next class, but right now you take it from me that or you many of you may already be also aware of this if the three-phase voltages are all 0 then the corresponding voltage vector is a null vector that is what we can say. So, you take it from me. So, this null vector can be applied using 2 different states that is one state is where all the top devices are ON and the other state is where all the bottom devices are ON.

So, essentially these are equivalent statements I am just saying that you can short the load by keeping all the top devices ON or the bottom devices ON. So, this corresponds to one state this corresponds to another state with they are called zero states these are zero states because you know there are no there is no power flow between the DC side and the ac side during these states and the load is fully shorted and it is the energy is simply freewheeling there and so in space vector terms it is just a different you know terminology. So, and in space vector terms what you are doing is you are playing a null vector you can say that you are applying null vector rather than saying that you are shorting the load and you know this is just an alternative statement now right.

So, it is another way of saying that is you can add a common mode component to the three-phase sine waves you have three-phase sine waves and you can add some common mode component to the three-phase sine waves now and this common mode component should consist of triplen frequency components. So, we have seen some examples of this earlier. One of the first examples we saw was you know a third harmonic frequency can be added if your fundamental is 50 hertz a modulation frequency is 50 hertz you can add a 150 hertz component a small of small amplitude to three-phase sine waves that is on example. We also saw certain other examples of common mode components in the previous lecture on bus clamping PWM. So, today in this lecture we would try to gain a better understanding of this particular thing that we are talking about right.

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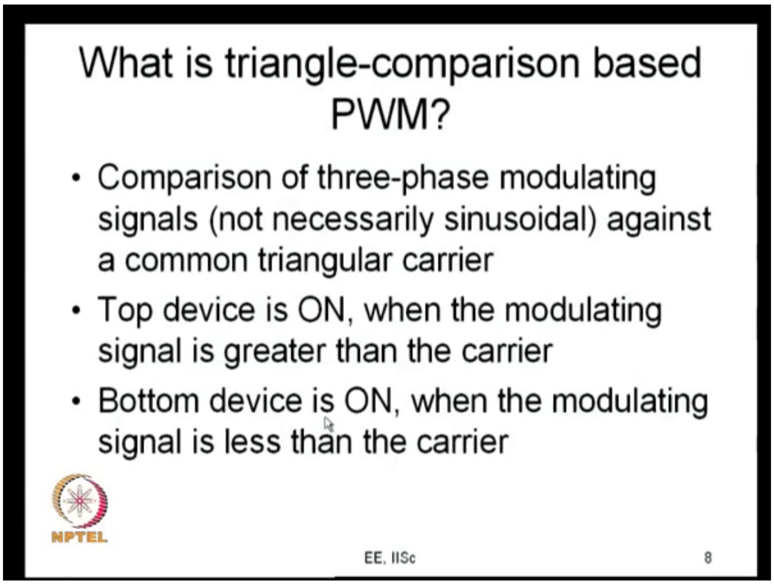

So, let us just say that since I said triangle comparison base PWM let us try and define that, what is this triangle comparison base PWM? It is one way of generating PWM waveforms, PWM waveforms are they getting signal waveforms that you are that are required to switch the device on and off. So, how do you do that? This method involves comparison of three-phase modulating signals what you have is you have three-phase modulating signals, whatever is maybe a signal there is a particular modulating signal for a particular phase that may be shifted by 120 degrees to get the modulating signal for the next phase and 800 and 120 degree to get for the signal for the third phase. So, you have a three-phase modulating signals and these three-phase modulating signals could be sign that is what is most commonly used I mean it is many atoms used, but not necessarily. So, it could be something else other than sign also.

So, you have three-phase modulating signals each, each of them corresponding to each phase and you compare these three-phase modulating signals against a common triangular carrier this is what you do for in triangle comparison based PWM. So, the triangle comparison you know gets its name from the carrier being triangular and the modulating signal are compared against a triangle carrier now. Now what do you do? You compare in the top device is on when the modulating signal is greater than the carriers the modulating signal is either greater than the carrier or it is less than the carrier. If the modulating signal is greater than the top device on if the modulating signal is lower than the bottom devices are on. So, this is what you do and in very very simple terms this is a description it is a very simple description of what is triangle comparison based PWM .

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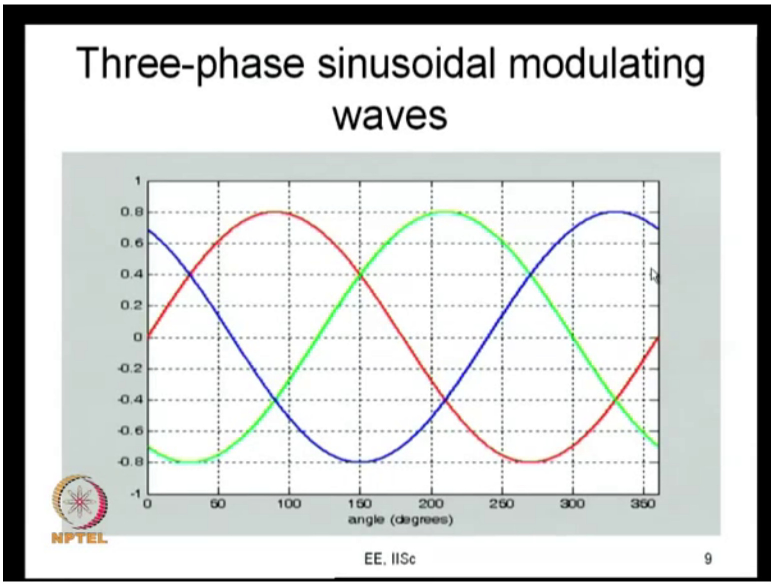

Now, you have known the simplistic case of three-phase modulating signals is three-phase a sinusoidal wave as you can see this is the R phase sinusoidal wave and the yellow phase I am just using green for better visibility and then this is what you have the blue phase signal right. So, you have R Y be the three-phase things. These are compared against a common triangular carrier and they would produce the PWM signals on the getting signals for the 3 legs the inverter, excuse me.

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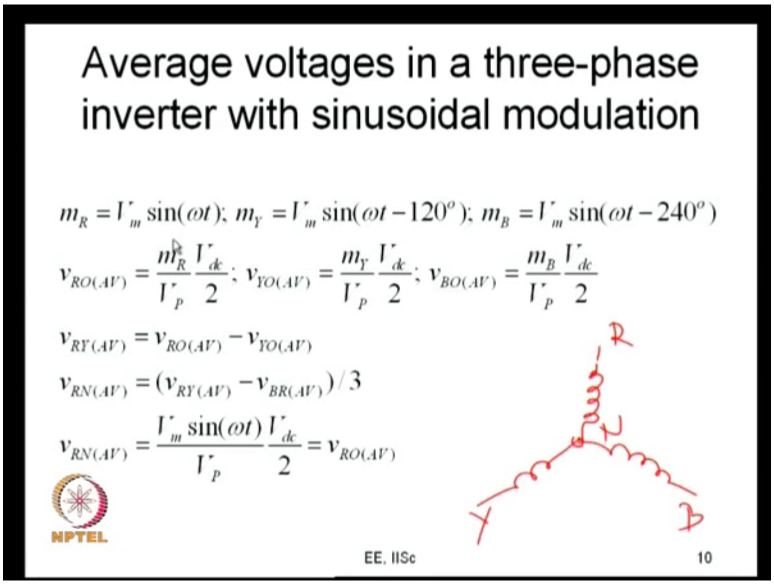

Now, we talk in terms of the average voltage in the three-phase inverter with sinusoidal modulation we considering sinusoidal modulation now. So, what do you mean by sinusoidal modulation? We have three-phase sine waves as we just saw in the last slide now I am just describing all this mathematically what is that let our three-phase signals I would call them as a m R I, can call them as a m Y, can call them as m B. And what is m R? I would say it is V m sine omega t and this omega is the modulation frequency and that is 2 pi f, if omega if f is 50 hertz it is 2 pi into 50 radians per second that is what omega is. So, it is V m sin omega t where V m is the amplitude now.

And the modulating signal for Y phase is V m sine omega t minus 120 degree and you can see that this is shifted in time by 120 degrees or one-third of the carriers I mean of the of the line cycle of the fundamental cycle and the B phase modulating signal is the same waveform shifted by another 120 degrees instead of 120 it is now 240 now.

So, it is V m sine of omega t minus 240 degrees now. So, this m R, m Y, m B is just the mathematical description of the 3 sine waves we just saw here now this is the mathematical description of these 3 now. So, what do we do now right. So, this is the modulating signal let us look at what is the so called average pole voltage let us break it up. Say pole what is pole? Pole is nothing but the midpoint of a leg because we said every leg is a single pole double throw switch and pole means midpoint of that the terminals R, Y and B can be called as poles.

Now, let us say R the voltage at R is measured with respect to o. So, what is o? o is the DC bus midpoint and now what is v RO, let us look at the instantaneous value? If the R phase stop devices on then v RO will be equal to this V dc by 2 its stop devices on when R phase bottom device is on then this v RO instantaneous voltage I am not talking about average yet the instantaneous will be equal to minus V dc by 2. Now what are we doing? In one half carrier cycle we are having the top device on for a while and the bottom device on for a while. So, sometimes it is plus V dc by 2 and sometimes it is minus V dc by 2 and your average voltage will be somewhere between plus V dc by 2 on minus V dc by 2 and this is what it is now.

So, whatever is the modulating signal value in that half carrier cycle divided by the peak of the triangular carrier m R by V p times V dc by 2 u. Let us take m R is equal to V p which is the highest value it can have during linear modulation if you are not going into over modulation even if you are going into over modulation any value in excess of m R is just ignored anyway. So, this is the highest value that we can look at is V p now. If it is V p then what they have v RO average is nothing, but V dc by 2 the average pole voltage is equal to plus V dc by 2. If m R is equal to minus V p then the average pole voltage is equal to minus V dc by 2. So, for any value of m R which is between mines V p and plus V p you will get some average pole voltage which is between minus V dc by 2, 1 plus V dc by 2.

The idea of average pole voltage is something that we have been carrying through from the time we discussed buck converter. Again you have an average pole voltage in the case of buck converter the average pole voltage is constant at steady state it is equal to the average output voltage now.

On the other hand we are talking enough DC to ac conversion here. So, the voltage at the pole is sinusoidal quantity this v RO average is proportional to m R, m R is sinusoidal quantity therefore, v RO average is a sinusoidal quantity. And what about v YO, v YO is also a sinusoidal quantity and x its it as the same amplitude as m R or you know the other R phase voltage excuse me has the same voltage that, but it is shifted in phase may 120 degrees now and once again you have v BO which is further shifted by another 120 degrees. So, you have three-phase average pole voltages and you can see that these 2 are simply scaled versions of one another m R and v RO average are just I know there is what is there is a scale factor what is that scale factor it is V dc by 2 V p. So, you can look at the inverter simply as a gain, the simplest model are the 0 at the model of an inverter would be just a gain and the gain is equal to V dc upon 2 V p where V dc is the DC bus voltage and V p is the peak of the triangular carrier. And remember we are using a bipolar carrier so the peaks are plus V p and minus V p here.

So, that is what is your invert inverters gain now. So, you have v RO average in v YO and v BO average. What are this? These are average pole voltages what do you mean by that the instantaneous pole voltage has been averaged over a carrier half carrier cycle that is what we mean by v RO average now right. These are the average pole voltages these are measured with respect to the DC midpoint o. Now what do we do next? Let us say we have v RY average this is the average line to line voltage, now what is average line to line voltage this v RY average is v RO average minus v YO vibration its very simple. If I take the instantaneous quantity v RY is equal to v RO minus v YO right. So, the same way v RY average is equal to v RO average minus v YO average you subtract those 2 quantities you get v RO average.

Now, the first quantity is sinusoidal second quantity is also sinusoidal and they are the same frequency they only have a phase difference. So, you know you will get another sinusoidal quantity of the same frequency v RY average, but its amplitude will be root 3 times the amplitude of v RO average that is what you have now. Now, let us say we have a three-phase load, let us consider a three-phase star connected load let us say our motor is there and this motor itself is let us say there is a three-phase winding like this, let us say this is R phase terminal this is terminal Y this is terminal B and this is neutral point this neutral n is the lord neutral and this is different from, this is different from the DC midpoint o. So, if you are in if you want to find out what is v R an average if the load is balanced then what you can do is v RN average is one-third of v RY average minus v BR average. And, so if you substitute all this values one into the other you will find that v RN average is equal to simply V m by V p times sine omega t V dc by 2 and that would be same as v RO average itself. This is a special case when you are talking of sinusoidal modulation your v RN average will be equal to v RO average whereas, when you start injecting common mode then this will no longer be equal as we will just see in the next slide now.

So, in the case of sinusoidal modulation you are using three-phase sinusoidal signals your average pole voltages are sinusoidal and the average line to line voltages which are the differences of, differences between the average pole voltages they are again sinusoidal and the average load phase to neutral voltages are once again sinusoidal and the load phase to neutral voltage v RN average is same as v RO average is what you want to see. In fact, this is the idea behind sinusoidal modulation now.

You want to apply let us say you know v RN average in v ON average this you want this to be sinusoidal, if you want this to be sinusoidal you have to make sure that this v RY average and v BR average v YB average have to be sinusoidal. If you want that then you what you can do is if you simply ensure that v RO average is sign and v YO average is sign then the difference between the two will also the sign. So, you can modulate v RO average v YO average and v BO average such that they are all sinusoidal of the same amplitude and they have a phase difference of 120 degree you can do that that is basic idea between sinusoidal modulation. If you want your v RO average to be sinusoidal have your m R to be sinusoidal now.

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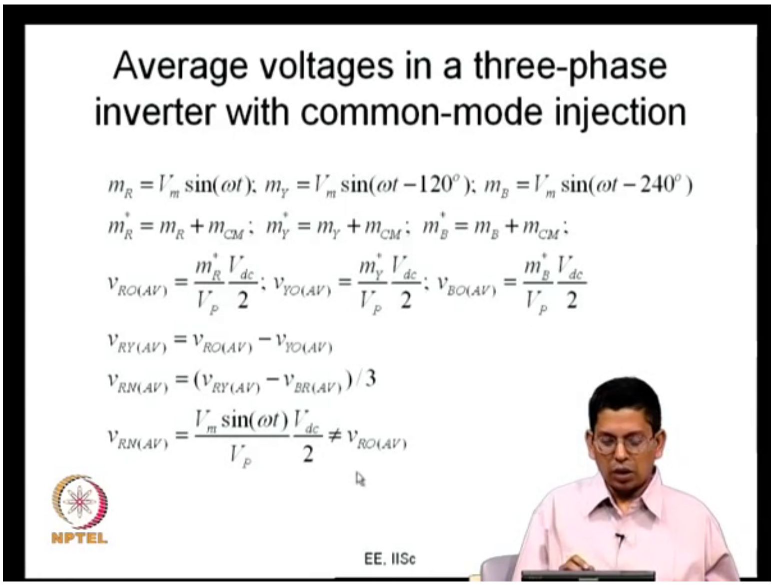

So, let us just look at the next level of complication here of you know next step of adding a common mode voltage now. Now once again you are looking at average pole voltages now that common mode added now. Let us we start from the same three-phase sinusoidal signals V m sin omega t V m sine omega t minus 120 and we excuse me V m sine omega t minus 240 these are three-phase voltages now. So, these are the same voltages this is what is the desired fundamental voltage this gives these are measures of the desired fundamental voltage now.

Now you take the liberty of adding some amount of common mode voltage now. Today we are trying to gain better understanding of what is this; what you know could be a suitable value of common mode voltage, you cannot add anything arbitrary that you want. We have some examples at least which could be common mode voltages we just want to do a little more of this now right. So, we are adding that and m R plus m CM is m R star, similarly my plus m CM is a m Y star, m B plus m CM is m B star. So, these are three-phase modulating signals with common mode added into them that is what you have now.

So, now what is going to be a v RO average your v RO average is not m R times V dc by 2 V p, but it is m R star you look at this m R star and what is this m R star it is a m R plus m CM. So, v RO average is no longer sinusoidal it is proportional to m R star which is not sinusoidal really, it is sine plus 1 common mode add component added to that now. So, your v RO averages you know is proportional to m R star v YO average is proportional to my star v BO average is proportional to m B star and this factor V dc by 2 V p can be taken as the gain of the inverter that is what it is.

Now, what do you get for v RY average, is v RO average minus v YO average something interesting happens here, what is that? When you subtract v RO average minus v YO average what your essentially doing is your subtracting m R star and m Y star and what is a m R star that is m R plus m CM and m Y plus m CM. So, if you subtract m R star minus my star the m CM in both of them the common mode voltage gets cancelled m R star minus m Y star is simply the same as m R minus my. So, the common mode vanishes though v RO average is non sinusoidally v RY average is still sinusoidal because the common mode components in both v RO average and v YO average gets subtracted because they are common mode it is the same thing that is there is been added to all the three-phases and so they get added they get subtracted from the line to line voltages now.

So, v RY average v YB average and v BR average three-phase line to line voltages are sinusoidal there is no common mode component in this right. So, you can add common mode component to the modulating signal and you know you can get away with that and it will not appear in the line to line voltages now. So, what happens? Now v RN average is the same thing one third of v RY average minus v BR average again this is assuming that the load is balanced. So, this is this simply comes from kvl again.

If you take v RN average what is your v RN average, now v RN average will be equal to V m sine omega t by V p into V dc by 2 which is not the same as v RO average; v RN average is actually equal to this m R is a m R divided by V p into V dc by 2 whereas, v RO averages is m R star into V dc by 2 V p and m R star is non sinusoidal v RO average is non sinusoidal whereas, v RN averages sinusoidal now.

So, this is what happens when you add common mode what your three-phase modulating signals.

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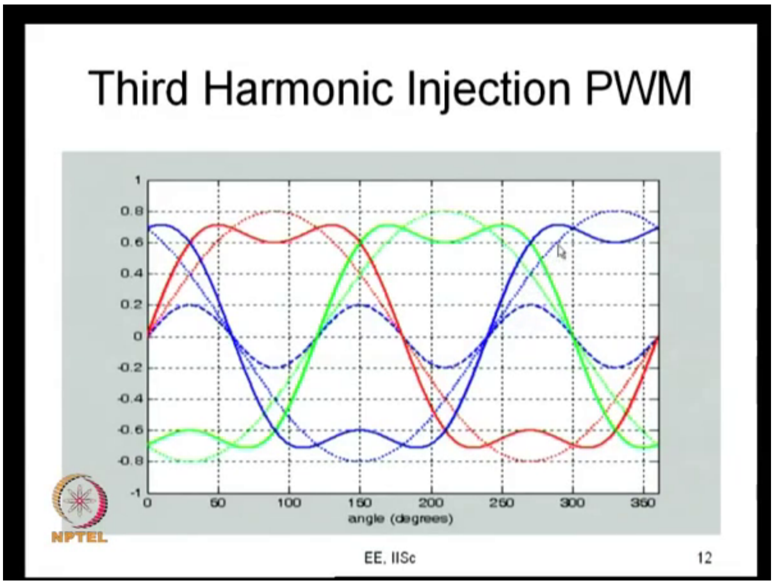

Now, on one very simple example of common mode is third harmonic injection which we have already seen now. So, you can see that this R phase is shown the R phase signal is shown in dotted lines red color dotted lines, the yellow phase sine wave is shown in the green color dotted lines, when the B phase sine wave is shown in the blue color dotted lines now you add a common mode component. And what is this common mode component? That is a small 150 hertz component like what is shown here in dash lines this is added to all the 3 sinusoidal signals.

So, your R phase signal for example, is now like this now. So, what happens the peak value comes down, that is whenever the R phase sign has its peak the common mode component I mean the R phase has a positive peak the common mode component is a negative peak. So, it brings down the total value now. So, it is something like its head has bend down a little.

So, you know your passing through the door and the door height is not very high the door frame height is not very high. So, you just gently bend your head and you get into that this happens in many old buildings in India. So, like that this is head is slightly bent here and so you can do this now. So, what you can defectively is you can see the peak value of the m R star is come down as I pointed out earlier. So, the peak value can go as high as the peak value of the carrier and therefore, this gives you know this is able to pack a higher amount of fundamental voltage and that is why it gives higher DC bus utilization as I pointed out earlier now.

So, this is now one example than what I am showing of a possible common mode component this has only a 50 hertz component as I said before and this is your m R and your v RN average will be proportional to this and this solid line is your m R star and your v RO average will be proportional to this.

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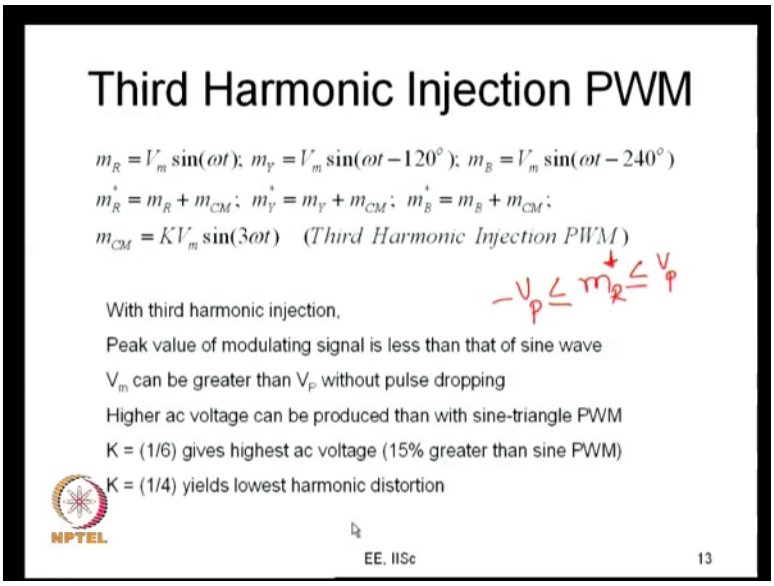

Then, let us look at you know this third harmonic injection just put it all mathematically whatever we have been saying before, you have start with the same 3 facing those m R my and m B these are sinusoidal signals and you had a common mode if m CM to all the 3 to get a m R star my star and m B star right.

Now, the common mode is a third harmonic sine wave and therefore, I am saying sine 3 omega t and what is its amplitude? I am calling it some KV m where K is a fraction. So, it is a small weight can be point one point 2. So, that is what it is now. So, with third harmonic injection as we just saw the peak value of the modulating signal is less than that of sine wave. So, it leads to the possibility that this V m that is the peak value of the sine wave can be greater than V p without pulse dropping, by pulse dropping what I mean is the value of m R star without the without the value of m R star exceeding V p are going below minus V p. So, if you look at in the previous case that is with this m R star peak value being less than plus V p or minus V p the highest value of V m that you can get is greater than V p, in fact, that value will be equal to 2 by root 3 times V p when you take K is equal to 1 by 6 now.

So, V m can be greater than V p. So, you can produce higher ac voltage that can you know sine than what you can produce with sine triangle PWM and K is equal to 1 by 6 gives the highest possible value that is he in this case V m can be 2 by root 3 times V p. So, 2 by root 3 is something like 1.15 roughly and so you can get 15 percent greater sign voltage the ac voltage then sine triangle PWM with the same inverter having the same DC bus voltage now. Actually you can you know this 1 by 6 is simply a factor being thrown at you, but this probably it is a good exercise for you to do this yourself as I mentioned in my lecture on third harmonic injection also.

So, what you are trying to do is this is your K you are trying to find out the optimal value of K the optimal value of K that will maximize this value of V m. So, subject to what constraint, there is one constraint that you have your m R star this is your m R star this m R star has to be less than or equal to V p similarly minus V p should be less than or equal to m R star. Similarly for my star m B star and my star and m B star sorry. So, you have this kind of condition to be satisfied by the 3 modulating signals. So, what you are trying to do here is you are trying to optimize scale find out the optimal value of K which would maximize this V m subject to this particular constraint, if you work out this problem it is a very simple optimization problem you will find that K is equal to 1 by 6 is the optimal value which can give you a maximum possible value of V m equal to 2 by root 3 times V peak. So, this is one value of K which is commonly used which is 1 by 6. So, this is from the point of view of maximizing the ac voltage for a given DC bus voltage you can get 15 percent higher ac voltage for the same DC voltage now

But again you know if you try to optimize in from the harmonic distortion point of view now you are trained to minimize harmonic destruction point of view. Previous studies have shown that K is equal to 1 by 4 or 0.25 is going to minimize the harmonic distortions, so this is what you are going to do now. We are not yet prepared to do this kind of an exercise, but later after doing space vector PWM we will develop some space vector base analytical methods for what you would call as analysis of current ripple you do some methods of analysis current ripple and while analyzing current ripple it will be possible for you to really work out something like this with K is equal to 1 by 4 you might be able to see that you are able you are getting a lower value of distortion now.

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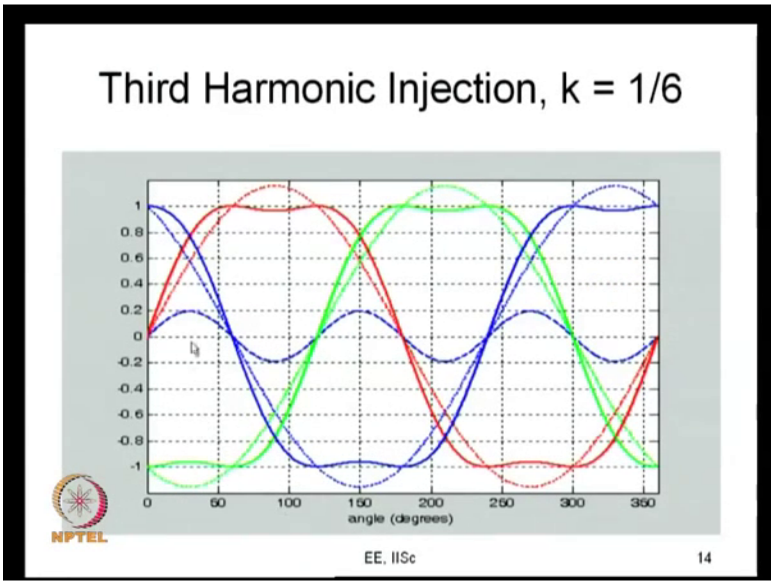

So, this is what I have just tried to show on K is equal to 1 by 6 I showed it previously probably and now, this shows that this is the highest value. So, here in this case the sine wave is now greater than 1 and that is actually equal to 2 by root 3 and you can see that the peak value of the modulating signal with common mode added is equal to 1. So, this is the highest and this shows the highest voltage AC voltage condition at which highest ac voltage is obtained for the same DC bus voltage now.

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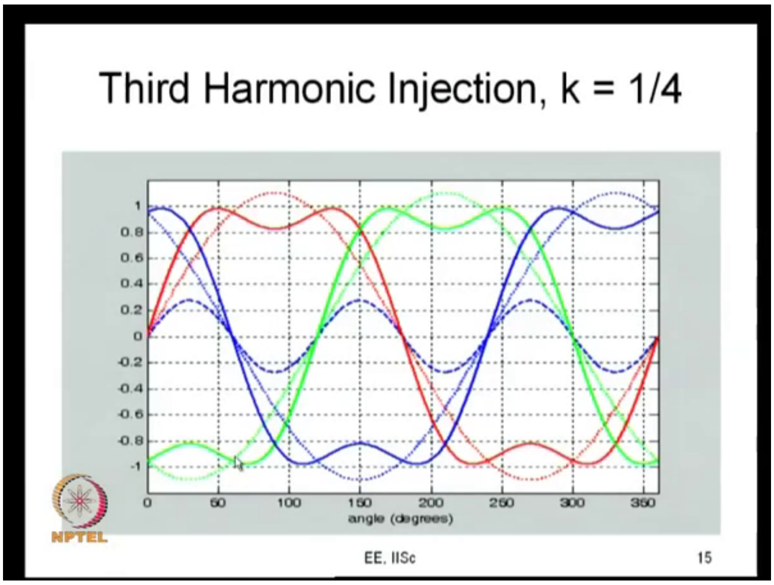

So, this is K is equal to 1 by 4 now you can see that here its again the modulating signal is touching 1, 1 stands for V (Refer Time: 30:10) that is the peak of the carrier and you can see that the peak value is a little lower now. In the earlier case the peak value was something like 1.15 something in this case it is a little bit clearly lower than that. So, with K is equal to 1 by 4 you can optimize the thd by minimize the thd, but you cannot really maximize the fundamental voltage that you can get. So, there is as we will discuss later conventional space vector PWM can achieve both right.

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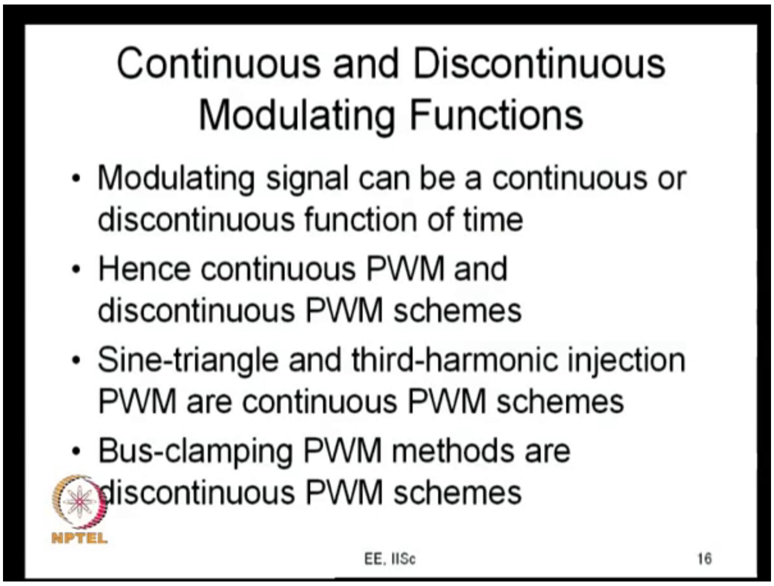

So, now you have looked at different kinds of modulating functions now. So, what we can see that the modulating functions can be continuous or discontinuous that they can be continuous function of time. What do you mean by continues and discontinuous? Function of, as a function of time, a modulating signal can be a continuous function of time or a discontinuous function of time if the modulating function is a continuous function of time you would call it as a continuous PWM scheme. If the modulating function is a discontinuous function of time you would call it as a continuous PWM scheme we first saw sine triangle PWM. So, the sine triangle we also sine we know for single phases of a three-phase inverter these are continuous PWM methods now.

And you know you can add even harmonics in the case of sine triangle PWM for single phase inverter we looked at both unipolar bipolar PWM and in unipolar we also added some even harmonics though even harmonic does not give you the benefit of increasing the ac voltage that can be produced. In fact, addition of even harmonic reduces the AC voltage that can be produced with that DC voltage in the case of single phase inverter in that sense it is not advantageous whereas, it is certainly advantages when you talk of three-phase and in the three-phase into third harmonic injection which gives you a higher ac side voltage now. So, the sine and the third harmonic injection are continuous PWM schemes. So, sine is a continuous waveform I mean this is a continuous function of time and in the third harmonic injection what you are adding is another sine waveform I am just start at 3 times the fundamental frequency. So, that is also a continuous function.

So, the common mode from is a continuous function of time and therefore, the resulting modulating signal is a continuous function of time in all the continuous PWM schemes. Sometimes you use modulating signals which are discontinuous functions of time the common mode component will be discontinuous functions of time yet you will often do when you want to result in bus clamping. So, when you want to resort to bus clamping as we discussed in the previous lectures and we will just look at it quickly now. So, in these cases the common mode signal is discontinuous and when this is added to the sine sinusoidal modulating waves you know the resulting modulating signal is discontinuous and these are called discontinuous PWM schemes now.

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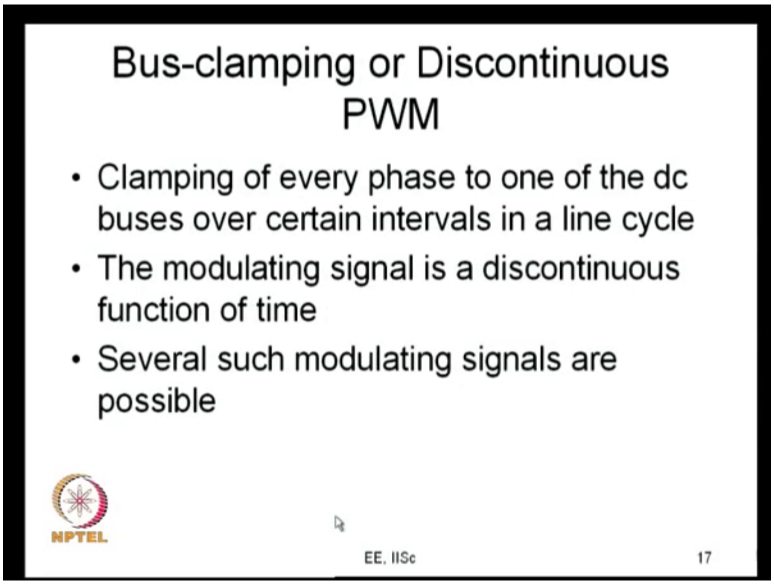

So, when you have bus clamping or discontinuous PWM what it usually does, it clamps every phase to one of the DC buses over certain intervals and they will in the line cycle and usually it will be a 60 degree duration you will find a phase clamp over to the positive DC bus for 60 degrees and you will find the same phase clamp to the negative DC bus for another 60 degree duration now. This case is modulating signal is a discontinuous function of time. And as we have seen even in the last class there are several modulating functions are possible.

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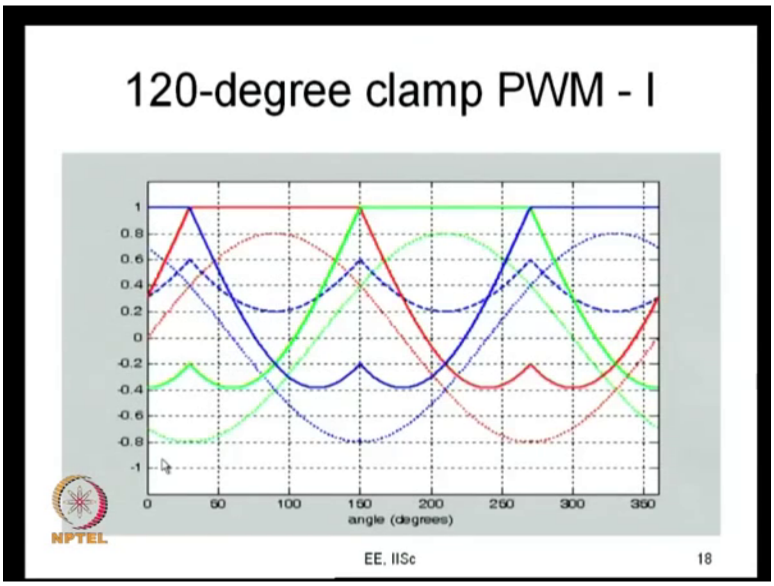

So, one of the modulating signal we saw was this 120 degree clamp what is call as 120 degree PWM I. So, you have this is your sine wave this is the R phase sign wave now and you also see the Y phase and the B phase sine waves are shown here now. So, what you are doing now is you are extracting the common mode component from the sine wave itself you take the sine wave whichever is highest and subtract it from V p.

So, for example, you subtract this and produce a common mode component and your common mode component is like this now. So, and we add this common mode to all the three-phases what happens is the resulting modulating signal is like this what is shown in the solid lines red line that is for the R phase modulating signal. You can see that the R phases clamped for 120 degree duration and similarly your Y phase is also clamped 120 degree duration and your B phase also clamped for 120 degree duration.

So, what happens here is it is never clamped the negative bus. So, you can see that the top devices have a higher conduction loss than the bottom devices and that is what we saw as a disadvantage in doing this now. Why is this happening? That is because you are adding a common mode component whose DC value is not 0 that is what we would (Refer Time: 34:24), so its DC value is not 0. If you look at the other alternative for doing this what you can simply do is you just go to the next step that is you can take the other modulating signal. In the first case you took the modulating signal which is maximum of the 3 modulating signals and you subtract it from V p, So, the difference between V p and the maximum modulating signal instead what you can take is the difference between the minimum modulating signal the one which is minimum of the 3 and minus V p and you a take that as the common mode signal this would be a common mode signal.

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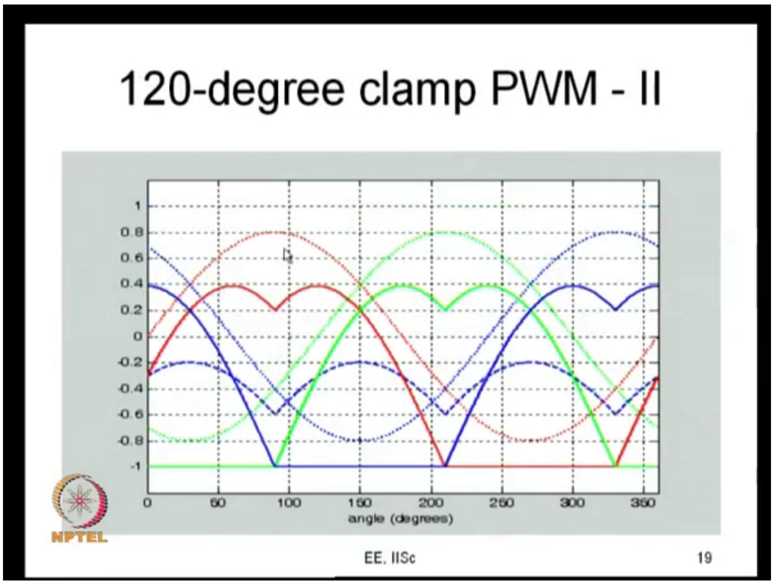

You add this common mode signal what you will get is as what you see here like this is shown for the blue phase now. You can see that the phase is clamped continually 120 degrees to the negative bus, phase would never get clamp to the positive bus. So, once again there is you know any even loading between the top and the bottom legs now.

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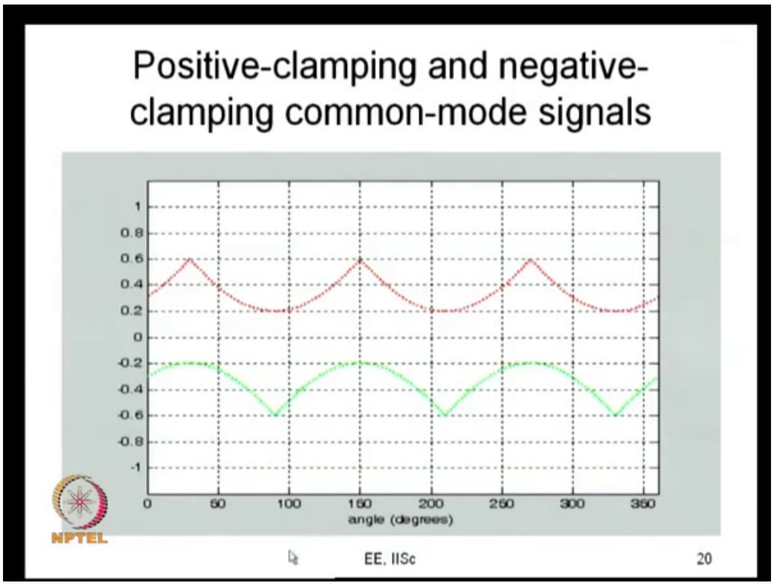

So, we have to get this clear, how to generate common mode signals which would result in bus clamping nevertheless would not affect the symmetrical operation of the inverter, that is all the three-phases should be loaded to the same extent and all the three-phases should be all the I mean both the top and bottom devices should be loaded equally. So, if you see there are only 2 possibilities for clamping you can clamp the phase which has got the highest modulating signal which is most positive or you can clamp the phase which is most negative which has got the lowest modulating signal excuse me. So, it goes on like this.

So, you can if you want to clamp to the positive bus then this is the modulating signal you can add if you want to clamp to the negative bus this is the modulating signal if you should had now. So, your option is always this or that, at any point you have an option you can either follow this or you can either follow this now. So, this would clamp a phase to the positive bus this would clamp another phase to the negative bus now. So, your question is how do you go about doing that now, and one there are several ways in which you can follow the two different waveforms all the different bus clamping methods are different examples of how you are doing this now.

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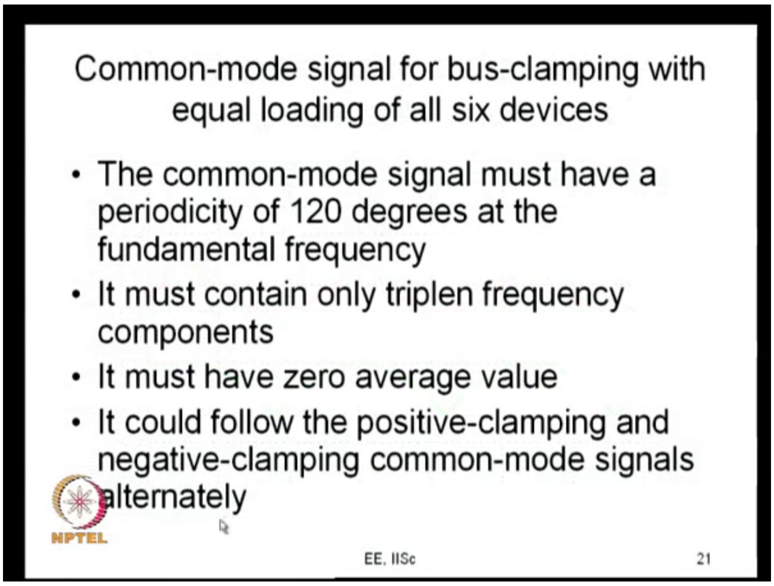

So, if you look at this certain rules here are the common mode signal must have a periodicity of 120 degrees now. So, if you see this itself is periodic by 120 degree this is also periodic by 120 degrees now, you have periodicity of 120 signals at the fundamental frequency it must contain only triplen frequency components. So, this is natural. So, if it is 120 degrees means fundamental at the fundamental frequency. So, it is its fundamental frequency is 3 times of fundamental. So, you know it is like 150 hertz or 50 as a modulation frequency. So, it will contain only triplen frequency components. And it must have zero average value. So, the average value of that should be zero that is sometimes you must follow the positive common mode signal sometimes you must follow the negative common mode signal and you should go between the two such that the average values zero, the average value at zero will ensure that the loading of the top and the bottom devices are equal.

So, it could follow the positive clamping and negative clamping more common-mode signals alternately. So, such that the value is zero, right.

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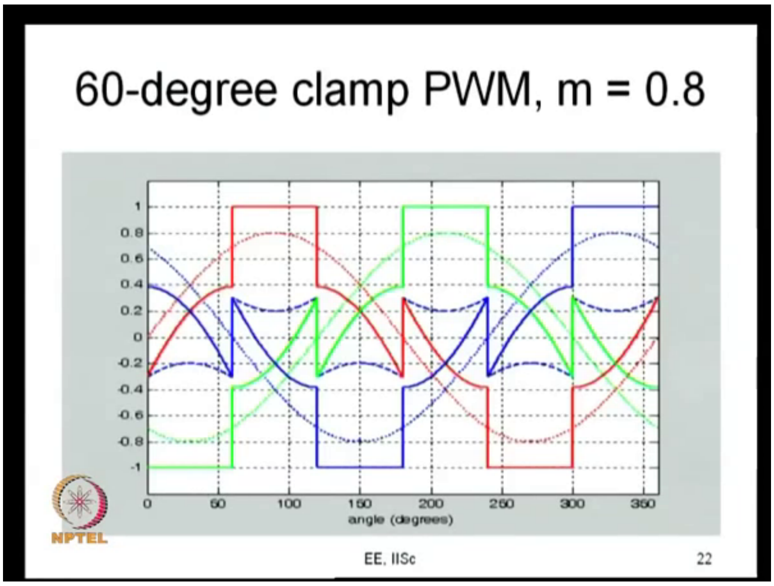

So, one example is 60 degree clamp what it does it follows the positive clamping for 60 degree and it follows the negative clamping for another 60 degree. Again it follows the positive clamping signal for 60 degree and then the negative clamping signal during the 60 degree and it clamps R phase for 60 degrees to the positive bus V phase to the negative bus for 60 degrees and then Y phase to the positive bus R phase to the negative bus and goes on like this now. So, this is what is called a 60 degree clamp on one example. So, you are following R and Y, I mean the positive and the negative common mode signals alternately for 60 degrees at the middle now.

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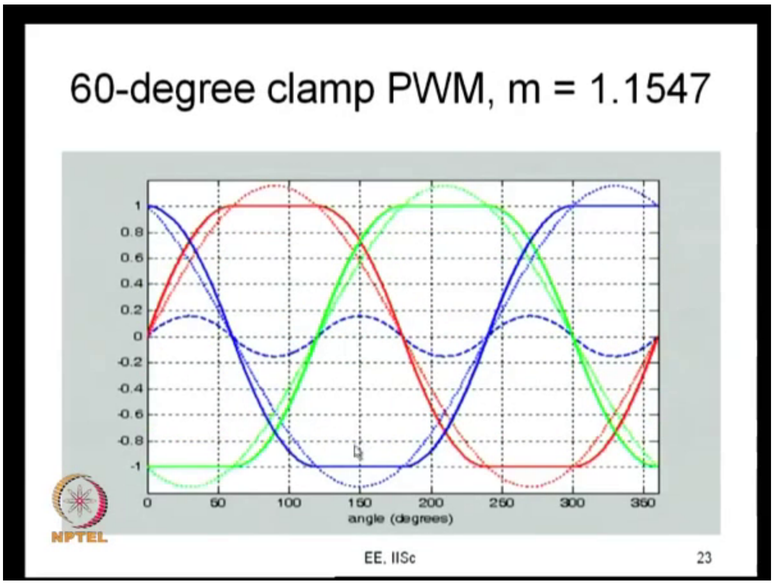

So, there is another. So, this is just the extreme case that is now I have shown here for a lower value of something like 0.8 I have shown V m is equal to 0.8, now here I am taking V m is equal to 2 by root 3 for that I am showing that this would be the resulting modulating signal. This is to show that 60 degree clamp can also work up to you know V m is equal to 2 by root 3 V p. So, you can have DC bus utilization as high as that of the third harmonic injection with K is equal to 1 by 6. So, you can work you can get 15 percent higher fundamental voltage than sine triangle PWM now and you look see that the common mode signal this is how it looks now.

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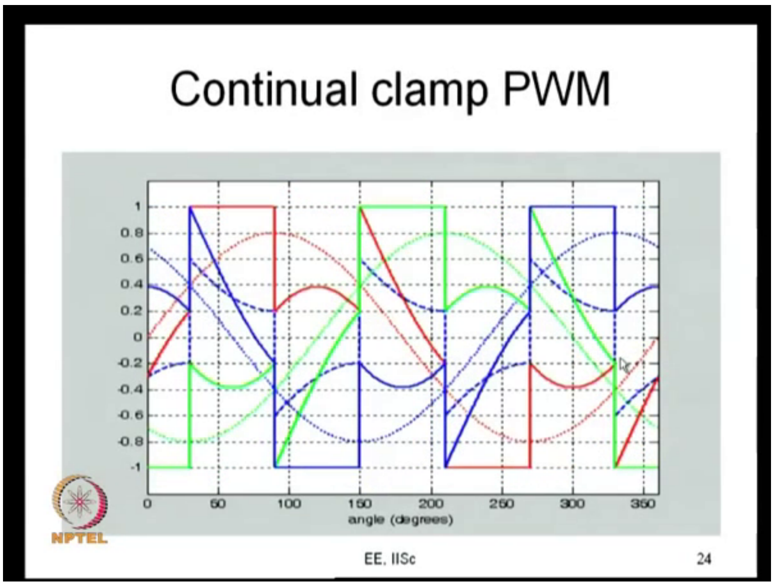

So, a generalization of 60 degree clamp is the continual clamp PWM, what you do is you follow the positive common mode component for 60 degrees and the negative common mode component for another 60 degrees, positive common mode for 60 degree and negative common mode for 60 degree and it ca n be positioned anywhere. In the earlier case it is positioned really at the center now that is from the 60 degree to 120 degree here the phase is clamped let us say from 30 to 90 degrees of the phase it is getting clamped now it can be positioned between 90 to 150 degrees of the phase also.

So, you can move around everywhere that is what happens here is now you can follow this like the middle 60 degree you can clamp and then you can come over here for the middle 60 degree you can go there to the middle 60 and come back to the middle 60. Now there is no necessity that it has to be middle 60 here and middle 60 there, what you can also do is you can follow this for 60 degrees here and for the next 60 degrees excuse me and the next 60 degrees you can follow here now. Then another 60 degrees you can follow this curve you can also follow like this now that is one case.

There is yet another case you start let us say you start from here you follow the positive curve for 60 degree and you follow the negative common mode component for 60 degree and go about being like this. So, these are all bus clamp. In general you can start from any instant here and go on for 60 degrees on this and go come on switch to the negative common mode go for 60 degrees and do this now.

So, this is what is called as continual clamping because so these are different examples of what you are doing here.

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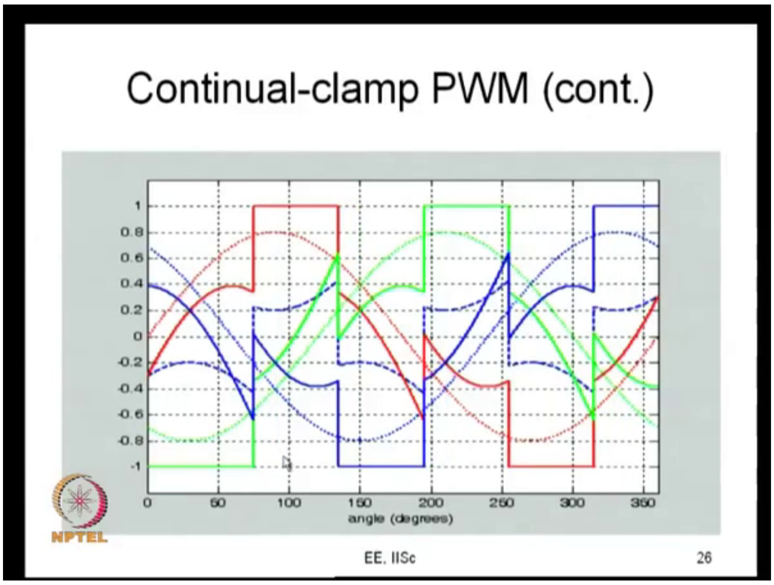

And in case of continual clamping what happens is the phase is continuously clamped of a 60 degrees to the positive bus and then for 60 degrees to the negative bus and so on, since it is clamped continuously for 60 degree which is called continual clamp it is just a nomenclature.

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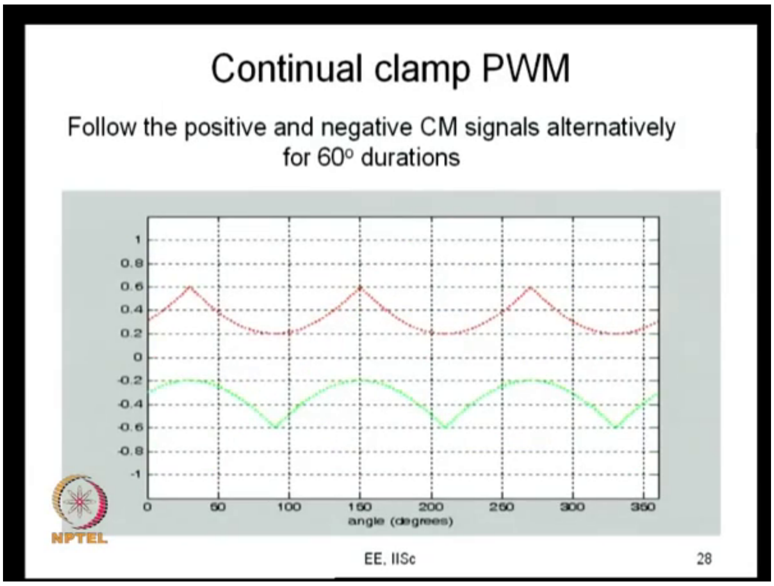

So, these are different examples of continuum clamp PWM now. So, as I said you follow the positive and the negative common mode signals alternately for 60 degree durations this is what you do when you want to go for continual clamp PWM now.

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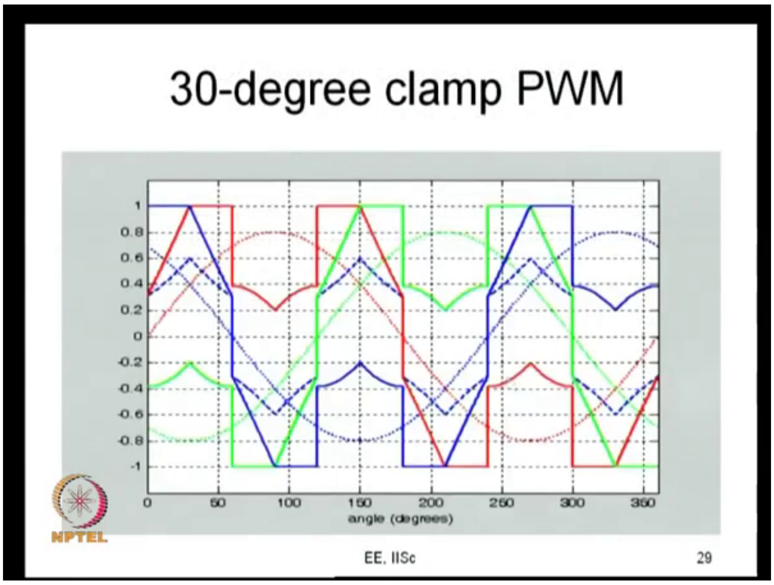

Let us go to the other thing of what is really called a sprit clamp PWM. Now I am just taking one example as you will show here now. So, here what we are doing is during this 30 degree duration we are following the positive clamp. So, it is getting clamped to the positive bus now and you know here what has happened is, this is 60 degree and here I know I am just making sure that the common mode added is now such that they are clamped to the negative bus now. So, in this case what happens the most negative value is Y phase up to this in this interval and subsequently the most negative value is B phase this interval now. So, in this interval the common mode makes sure that the Y phase gets clamped on the negative bus in this interval the common mode make sure that it gets clamped right B phase gets clamped to the negative phase now.

And after this what happens you again move back to the positive common mode component now, if you move back to the positive common mode component what happens is R phase is the most positive and the common mode component is difference between V p and the R phase voltage R phase gets clamped to 30 degrees now. In the middle what happens you are still following the positive common mode component now the positive common mode component now basically comes from here. So, first your common mode component is difference between V p and this signal and, the next phase Y phase gets clamped to 30 degrees now.

So, here what happens R phase is clamped to positive bus for 30 degrees and here again for 30 degree, this is between angle 30 to 60 degree and this is between angle 120 to one 50 degrees since they are clamped for 30 degree in every quarter cycle instead of 60 degree in every half cycle here it is 60 degree in every half cycle here it is 30 degree in every quarter cycle and therefore, you give a name called 30 degree clamp PWM now.

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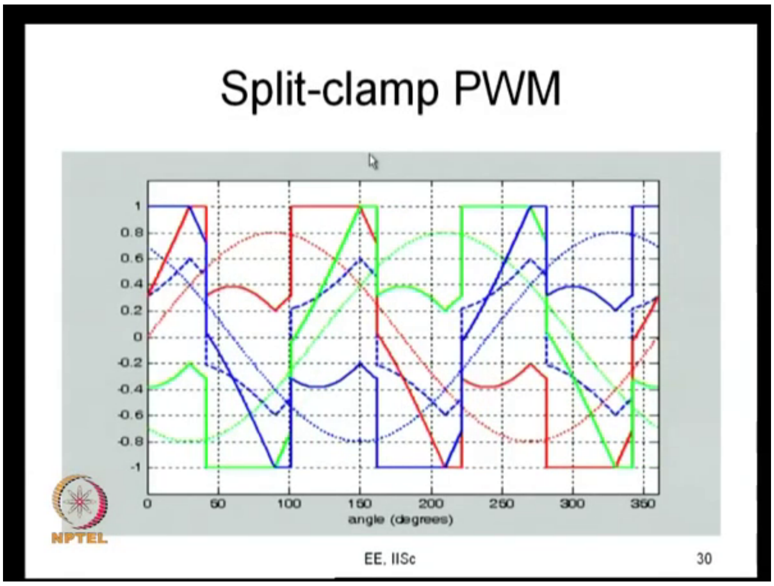

So, a generalization of this 30 degree climb PWM is split clamp PWM now. So, instead of 30 degrees and 30 degrees this can be some gamma and some 60 minutes gamma. So, they will add up to 60 degrees now.

So, this is a particular case and this is not been very well studied till now, I mean there very limited studies on this 30 degree clamp is widely known, but the generalization of 30 degree clamp name is split clamp is not so well studied now. I will come back to this when I deal with this bus clamping PWM from the space vector perspective also. It is split clamp PWM is not very easy to be seen from the three-phase modulating signals, but it is much easier to be seen from the space vector point of view. So, I will just touch upon that when I deal with that in the space vector P based PWM lectures.

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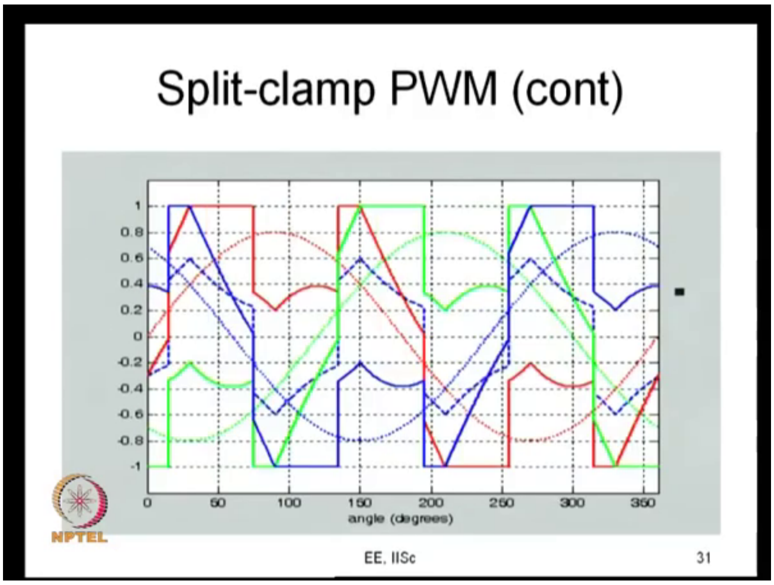

So, now, this is all different examples of split clamping PWM this is one case where you know if this clamping duration is small here and long here, but the total clamping duration is 60 degree. This is the clamping duration here is long and here at a small, but again the total clamping duration is 60 degree.

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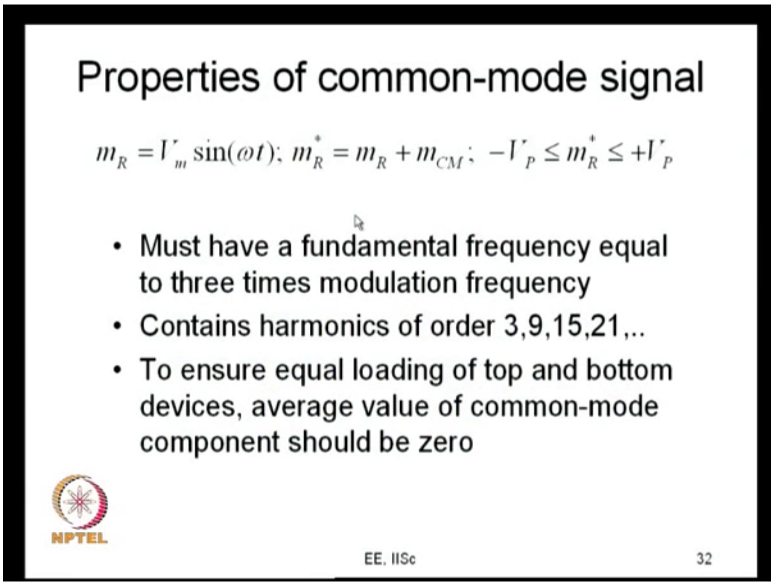

So, it goes on now, just having a relook at the properties of the common mode signal. So, what we know is there are different kinds of common mode signals are there and you can add various common mode signals that is how what we have been looking at. So, triangle comparison based PWM means what, you compare three-phase modulating signals against a common carrier and what does that three-phase modulating what is the modulating signal it can be sinusoidal or it can be signed with some common mode signal added.

So, we just have to be clear as to what kind of common mode signals should be added. So, you have V m sine omega t, I am not writing down the modulating signals for the other 2 now you are adding common mode the same common mode is added to m Y and m V also to produce m Y star and m V star which I am not giving here now. The common mode added should be small it should be small such that the resultant m R star should not you know it does not go beyond plus V p or minus V p. So, minus V p less than or equal to m R star less than or equal to plus V p is one of the constraint. So, the common mode amplitude has to be small enough such that this constraint is right.

Now, on top of this what should you do? The common mode component must have a fundamental frequency equal to 3 times the modulating frequency that is the common mode components periodicity should be 120 degrees of the fundamental now only then if you know it is you know it what is added is coming to all the three-phases now. So, this is another condition and this condition naturally means you know it has a only the triple n frequency components like 3 6 etcetera and usually this common mode component many times will have a half wave symmetry let us just look at that you know let us say you look at a common mode point where it is clear. So, this is a common mode component off.

So, this dashed line is common mode component and you can see that it has got one it has got 120 degree periodicity the periodicity its periodic or 120 degrees now and you take this half way when this half way we can see that is symmetric now that is the common mode component value at theta and its value at you know it is 120 degree and its half period is 60 degree. Its value at theta and its value at 60 plus theta are the negative of one another. So, this waveform has half wave symmetry this waveform itself has no even harmonics and therefore, what you will find is it will not have 6 12 24 etcetera it will have third, ninth, 15th, twenty first etcetera. So, because this is a waveform of fundamental frequency and off whose periodicity is one third of the fundamental and, therefore, it has and it also has half wave symmetry. So, it has harmonics of the order 3 9 15 21 etcetera.

And then what you have to do to ensure equal loading of top and bottom devices you have to make sure that the average value of common mode component should be equal to 0 this is again one factor that we have to. Subject to these constraints basically it is possible for you to generate several kinds of common modes; the only question is what is the advantage in adding a common mode.

One advantage would be that I you know some common modes can give you addition of you know like a increase DC bus voltage, sometimes I can give you a reduction in the pulsating torque and so on and so forth. So, what I am trying to say is you can examine some more common word signals you know like this these are you knows they are possible and what I have indicated are all popular examples and which have been useful in some particular sensor the other. So, if you want to go into some more investigations you just have to make sure that these are made so that this would basically ensure that you are adding a common mode signal which would not take the inverter into or modulation which will keep the still in linear modulation, it will not go into what is called as pulse dropping and it will make sure that all the three-phases are loaded equally and it will make sure that the top on the bottom devices are loaded equally right.

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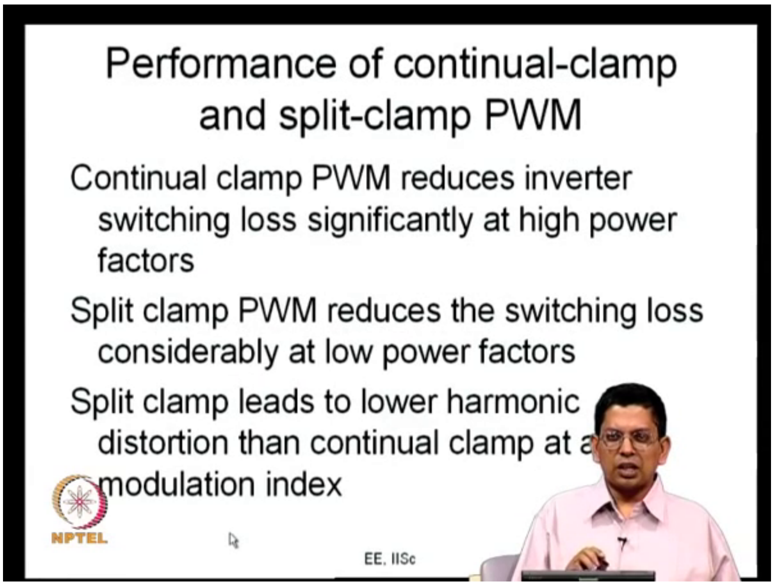

So, just some general remarks about the performance of continual clamp and split clamp PWM of course, at this point of time we have not developed the necessary analytical tools for us to be able to analyze and compare continual clamp PWM and split clamp

PWM. So, it is more real kind an assertion that I am making now. And at you know during when we are in a position to analyze the current ripple and etcetera we will be able to probably later on will try and develop some analytical tools during that time it will be possible for us to make better sense out of the claims that are being made here now, nevertheless these are facts which have been established discussed in the literature now.

So, if you take continual clamp PWM and split clamp PWM where continual clamp a phases clamped continuously for 60 degree duration in every half cycle and in split clamp PWM a phases clamped for some duration gamma and 60 minutes gamma which has, so they add to 60 degree in a particular half cycle. So, it is clamped for some duration gamma in the first quarter and 16 minus gamma at the second quarter. So, the clamping durations is split into 2 gamma and 16 minutes gamma hence the name split clamp PWM. So, what has been seen is continues clamp PWM reduces inverter switching loss significantly at high power factors that is let us take one continual clamp PWM the simplest is 60 degree clamp PWM. So, you take here now.

So, what happens here R phase is not switching at all here and what is the R phase fundamental voltage it is simply proportional to this now. Now let us say the load is unit above factor the ac set load is a unity power factor load. So, the current will also be in phase with the voltage now. So, what happens when the current is at its close to its peak the phase is not switching and the switching loss an every time you turn on and turn off a device that is going to be last and what does that last depend on one thing it depends on is the DC bus voltage its almost directly proportional to DC bus voltage and it is also roughly proportional to the current that is being switched now. Therefore, let us say when now this is the voltage waveform let us also assume this to be the current waveform the unity perfect load if you are switching this phase when the current is very low the switching energy last is very low, on the other hand if you are switching the phase here when current is high the switching energy last is high.

Now, if your load is unity power factor load this 60 degree clamp PWM makes sure that you are not switching that particular phase when its current is very high and therefore, it results in a substantial saving of energy that is lost and therefore, you can say for unity power factor cases are power factors close to unity the 60 degree clamp is very very is a good option it reduces switching loss now. So, you can say that here the clamping is between 30 to 90 degree.

Let us say when the load is slightly leading. So, the current is leading the phase voltage again. So, this kind of 30 degree clamp PWM where the clamping is from 30 to 90 is going to be advantageous now. Let us say if it is lagging to load as it is the case in the case of induction motor drives you can simply clamp between 90 to 150 degree. In induction motor drive since it is by enlarge you know if this is a good option this PWM method why, the phase voltage is like this and the phase current will lag the phase voltage. So, the phase current will have its peak somewhere in this region and in this region the phase will be clamped and therefore, the switching energy last is slow.

So, from switching last point of view this method can be a good method for motor drives. So, you can actually place the 60 degree duration anywhere you want within the 120 degree interval now. So, you can do it precisely according to the power factor when the power factor is very high, when the power factor angle is between minus 30 to plus 30 degree you can make sure that the phase is clamped whenever the current is around its peak now.

So, these are very good for high power factor loads. So, that is the claim that is being made here continual clamp PWM reduces inverter switching loss significantly at high power factors. On the other hand split clamp PWM reduces the switching loss considerably at low power factors this is been reported in some recent papers including the reference that has been mentioned here. So, what happens in split clamp PWM is let us go to the 30 degree clamp now here what happens R phase is clamped here and Y phase again R phase is clamped in there let us say you consider 0 power factor load. So, the load voltage is 0 in case of 0 power factor load the current is going to be at its peak, so the load current is going to be at its peak now.

So, from the peak let us say it is falling down to 0 like this. So, it is clamped when it is clamped the phase is clamped when the current us between 0.866 times the peak to 0.5 times the peak. So, whenever the phase current is between 0.5 times the peak value and 0.866 times the peak value it is getting clamped now. So, this results in a substantial amount of saline though you are not able to clamp the phase exactly when the current is going through the peak you are able to clamp it whenever the current is between 0.5

times the peak and 0.866 times the peak and therefore, this is able to reduce it some amount of switching energy loss.

So, this is I get to you know I am just trying to say why this is true split clamp PWM reduces the switching loss considerably at low power factors. So, this has advantage at high power factors and this is advantage at low power factors from the switching loss point of view because bus clamping PWM itself is one idea that you often use to handle this issue of switching loss now.

The next question is about distortion if you compare the 2 in terms harmonic distortion split clamp PWM leads to lower harmonic distortion then continue clamp, but any given modulation index you take some value fundamental voltage like 80 percent of the 6 type voltage are 70 percent of 6 type voltage. You can use split clamp PWM you can also use continual clamp PWM what you will find this split clamp PWM leads to lower harmonic distortion than continues clamp PWM is what you will see now. Again at this point we do not have the necessary analytical tools in place to understand this particular statement in any greater detail nevertheless this is a fact I am hoping that it related it after we have discussed phase vector base PWM and after we have discussed there how to evaluate line current ripple etcetera we would be able to revisit this question and understand why split clamp PWM leads to lower distortion than continual clamp PWM.

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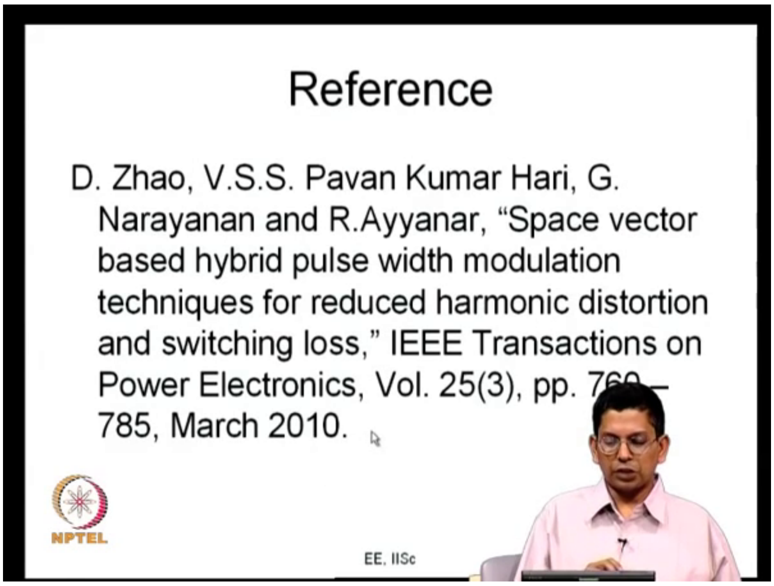

Now, this for further references here, this particular paper it is basically more an advanced bus clamping PWM methods and it is not so much on bus clamping PWM itself, but still it has certain details about bus clamping PWM. So, I would suggest this particular reference which I have also given in some earlier lectures D Zhao V.S.S Pavan Kumar Hari, Narayanan and Ayyanar this is space vector based hybrid pulse with modulation techniques for reduced harmonic distortion and switching loss published in IEEE transactions on power electronics in the March 2010 issued. So, this is what we have essentially, so this has further references on this.

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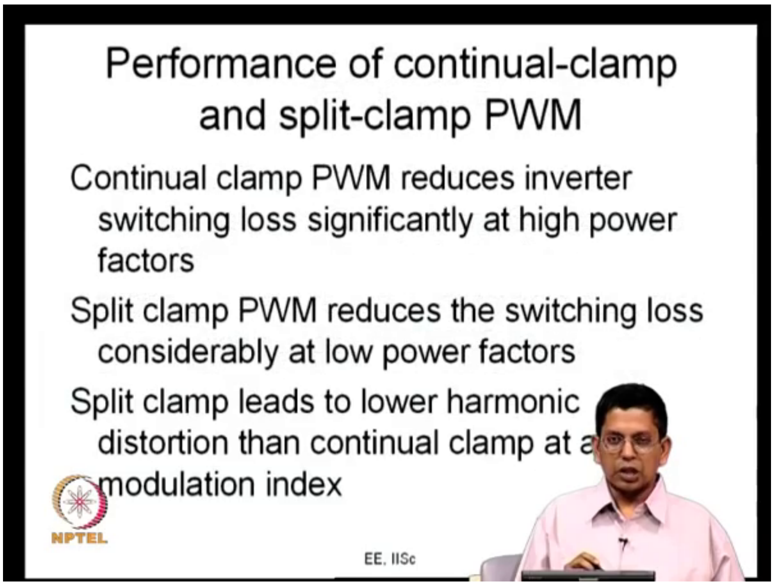

So, what we would be doing in the subsequent classes we will be going into space vector base PWM. So, what we looked at right now is different kinds of common mode signals that really can be added to the three-phase signal and our basic thing has been to move over to let say what we looked at from the previous picture that is we looked at a particular way of modulation that is triangle comparison base modulation.

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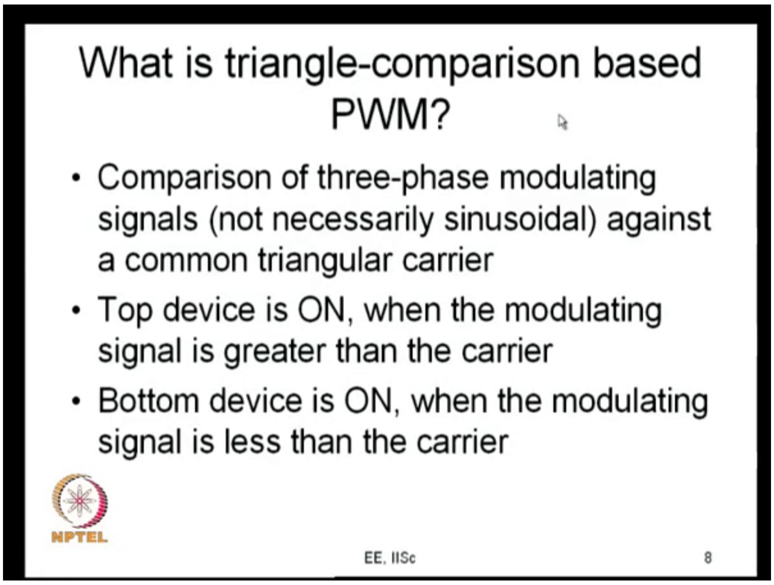

What we looked at is could the way of producing the PWM signals by comparing three-phase modulating signals. So, every phase has got a particular modulating signal and it is compared against a triangular carrier and you know by this triangle intersection you are producing the PWM pulses. So, this is something called per phase approach for every particular phase you are having a particular modulating signal. The alternate approach is to look at all the three-phases together what I would call as space vector PWM. You look at we will next class what we will do is we will go about defining what is called as a space vector and then we will design define what is called a space vector transformation. So, that is how you can transform three-phase voltages into what is called as a voltage space vector and now based on the space vector idea we will develop modulation methods.

So, I would say there are two possible approaches which are commonly used for producing PWM generation. One very popular approach is triangle comparison PWM. So, this is been there around for about 3 4 decades now longer than that and space vector base PWM is relatively you are it you know you could say that it started being used from the middle of 80s or so and that is space vector based PWM. So, that is what we will be discussing in the next class now.

This triangle based comparison based PWM is originally sine triangle PWM and then there are variants of sine triangle PWM and sine triangle PWM you can say it has its it had its origin in the modulation theory that is when you kind of modulate two different signals what happens sign modulation, similarly you can look at sine triangle modulation it started from there. In the space vector theory on the other hand I would say had its origin in generalized machine theory that is you can start looking at revolving space vectors.

We are familiar with time phase right that is you have several quantities which are sinusoidal like the signals that we use sometimes or sinusoidal signals whenever a quantity is sinusoidal you can represent it as a time phase and you express it as a revolving phaser now. You can also think of revolving vectors mean revolve in space for example, you take a three-phase machine and the three-phase machines MMF is revolving right. So, that is an example of a space vector. So, now we are having space triangle comparison based PWM. Similarly we will be going into what we call as a space vector based PWM that would be an alternative approach.

So, the next 3 or four lectures we would look at what space vector PWM that would be the next module that we will be dealing with and subsequently what we will be trying to do is we will trying to kind of compare the space vector base PWM and triangle comparison base PWM and we will be getting and trying to get a good picture of what exactly we want to do now. So, meanwhile I just go back and I just give you this reference which I just indicated to you now and I hope this particular lecture was helpful for you and hoping to see you during the next lectures.

Thank you very much.