Pulsewidth Modulation for Power Electronic Converters
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Lecture - 33
Design of PWM for reduced switching loss in three-phase inverter

Welcome back to this lecture series on Pulsewidth Modulation for Power Electronic Converters. We have done 32 lectures so far, this is the 33rd lecture today in this lecture series. So, we have done several of this modules as you have already seen there are about 8, 5, 9 of this modules have been completed and we are now the 10th module.

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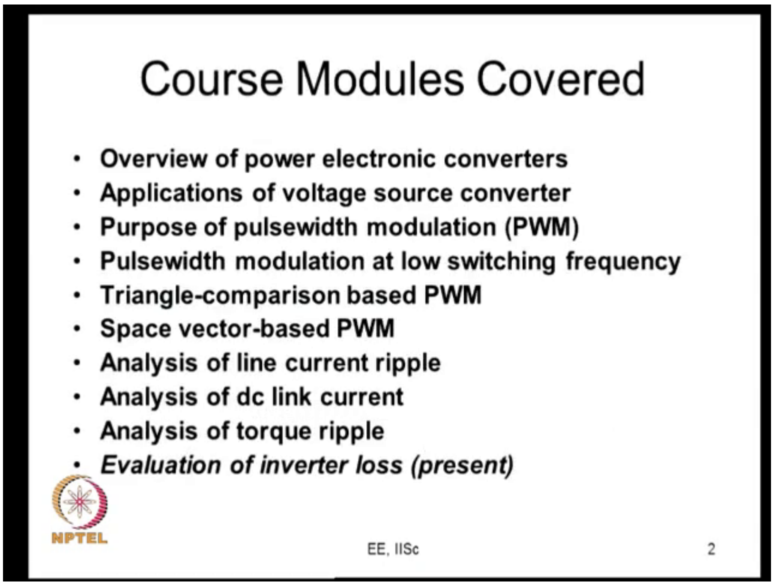

So, the earlier modules first it this module first focused on the topology in DC AC converters, and the second module focused on the few applications of voltage source converters, third module focused on certain fundamental things in basic principles pertaining to pulse width modulation.

And the forth module focused on generation of PWM at low frequencies. The fifth and sixth modules focused on generation of PWM waveforms at higher switching frequencies, when the inverter switching at frequencies much higher than the fundamental frequency desired.

So, there are two different approaches one is triangle comparison and other one is space vector based PWM. As I have said many times before whatever is possible with space triangle comparison based is possible with space vector, but it is not possible wise there are certain space vector based PWM methods which cannot be implemented as triangle comparison methods.

So, space vector based PWM is more general than triangle comparison PWM methods, but triangle comparison PWM methods could actually be easier to implement. So, we have seen the many of these. So there are continuous and discontinuous bus-clamping PWM methods or discontinuous PWM also we call it as bus-clamping PWM. These continuous and discontinuous PWM methods can either be implemented as triangle comparison methods or a space vector methods many a times it might be easier to implement them as triangle comparison methods.

But there are certain PWM methods called advance bus-clamping PWM methods so they rely on certain flexibilities offered by the space vector based PWM. The triangle comparison based PWM is based on the flexibility that the null vector time there is a null vector produced by the inverter and that is applied using two different zero states. So you know the null vector time is divided between the two zero states and there is a degree of freedom there or in other words there is edition of common mode voltage. Whereas in space vector PWM you can have that division of null vector time between two zero states and also you have the freedom to apply an active state more than once.

So, there is what you can call as division of active vector time also so there is certain additional degree of freedom available in the space vector based PWM method which leads to what we call here as advance bus-clamping PWM methods. So, these advanced bus clamping PWM methods they result in bus clamping just as the discontinuous PWM methods do. So, phase would not switch in some region of the fundamental it would switch at the nominal frequency in certain other region and it would switch at double the nominal switching frequency in some other regions. So these are advance bus clamping PWM methods. We discuss some advance bus-clamping PWM methods as part of our the space vector based PWM.

And we did analysis of the PWM methods continuous discontinuous and advance bus clamping PWM methods to certain extent in this module on line current ripple. So we showed that there are certain conditions where the advance space vector based PWM could be better than the other methods particularly in terms of line current ripple at high modulation indices.

And we also showed that some advanced space vector PWM methods could actually be better in terms of torque ripple in this particular module. We also tried to evaluate the dc link current for various methods and we showed that the dc link current I mean the rms value of dc link current is actually largely independent of the PWM methods that you really used now.

So, after having covered these modules we have been dealing this module on evaluation of inverter loss this is on account of the non-idealities in the switches. We are still not considering the I mean the losses in the passives and all that which you_can easily find out for example, the if there is a filter inductor and there is certain amount of current flowing through that the filter indicter would have some resistance internal resistance let us call it r, and you know you can actually calculate the loss in this inductor using this you know with the knowledge of the rms current through the inductor.

Similarly if there is a capacitor here we were able to find the dc link current and the capacitor current. So, we can find out the rms current capacitor current so the rms capacitor current and the equivalency there is a resistor of the capacitor can give us the loss in the capacitor.

So, here our focus is been on the essentially the semi conductor devices in the inverter. So, there are two significant kind of losses, one on account of the forward conduction, so like which is called as conduction loss which is on account of the forward drop and the other losses on account of switching. So, when there is a switching transition there is a certain amount of power dissipation there is some movement of energy loss.

So, in the first lecture in this module we focussed on the conduction loss, and the second lecture we focussed on switching loss, today you know we also found that the PWM methods you know the variation on of the conduction loss with PWM is not too high. So, because you know always either a transistor or another diode conducts so there is some influence but it is not too high, whereas the influence of the PWM method on the switching loss is very high particularly for the discontinuous PWM methods not for the continuous PWM methods, but for discontinuous PWM or bus-clamping methods and also for advance bus clamping PWM methods. So that is something we discussed in the last lecture.

So, today we might get a clearer idea of this effect of the PWM methods on switching loss and we would also actually try and design some PWM methods which would reduce the switching loss compared to standard methods such as conventional space vector PWM. So that is what we will be doing in today's thing that is in the present module in the last lecture of this module.

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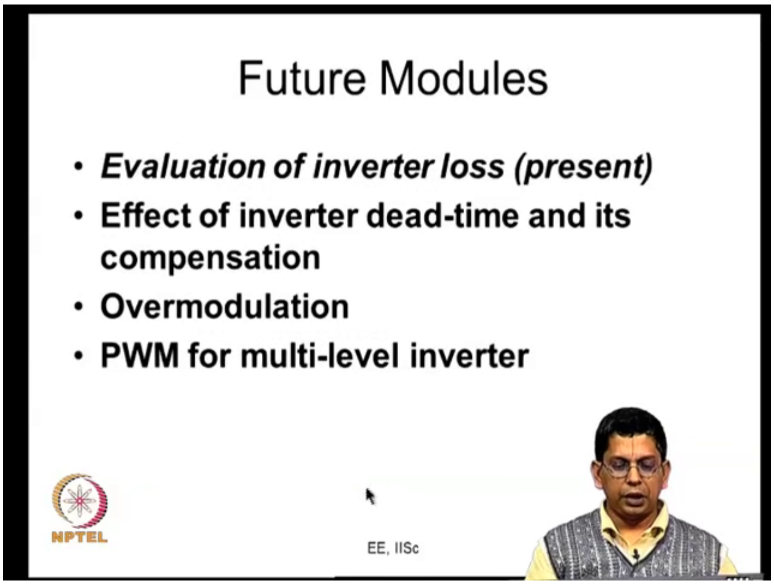

And in the subsequent modules we will focus on the inverter dead-time it is effect on over modulation PWM for multi-level inverter.

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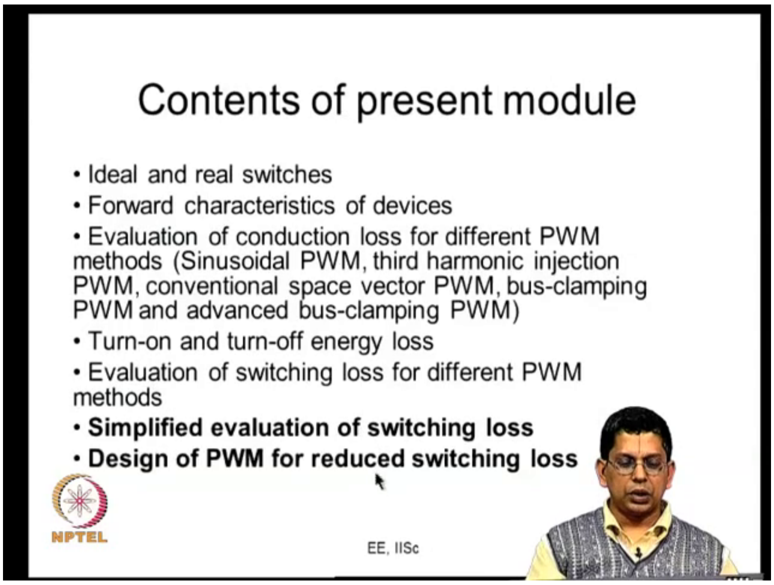

So, as I just said before we covered all this aspects in the previous lectures that they you know there are ideal switches, there are real switches, real switches have forward drop and therefore you know there is some finite amount of conduction loss and we tried evaluating this various conduction loss for the I mean different PWM methods, I mean we discussed how to evaluate the conduction loss for the different PWM methods and we discussed turn on and turn off energy loss, and we tried to evaluate the switching loss for different PWM methods we mean how to go about switching.

So, today what we will do is this is based on the turn on and turn off energy loss which is the function of the operating conditions for example, if a device is turning on and you know there is certain amount of dc bus voltage, there is certain amount of current that it has to conduct and it is operating at some temperature so all this would decide on how much is the turn on energy loss.

Today what we would do is we would simplify that basically we would simplify that you know turn on energy loss and the turn off energy loss we would rate down more directly to the current that is being switched so and which that simplification we could actually do a comparative evaluation of different PWM methods more conveniently and easily. And then we would use that idea to design PWM methods which can actually reduce the switching loss so this is what is going to be the focus for today's lecture.

So, let us we call this as design of PWM for reduced switching loss in three-phase inverter alright.

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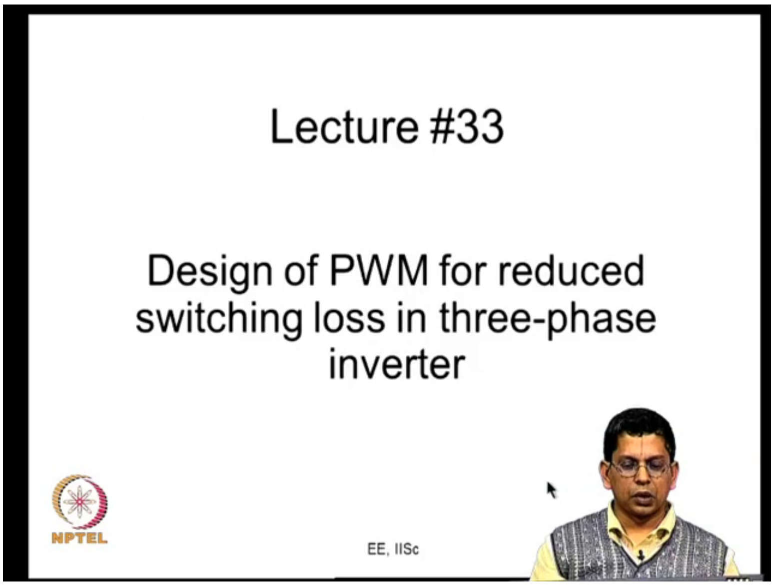

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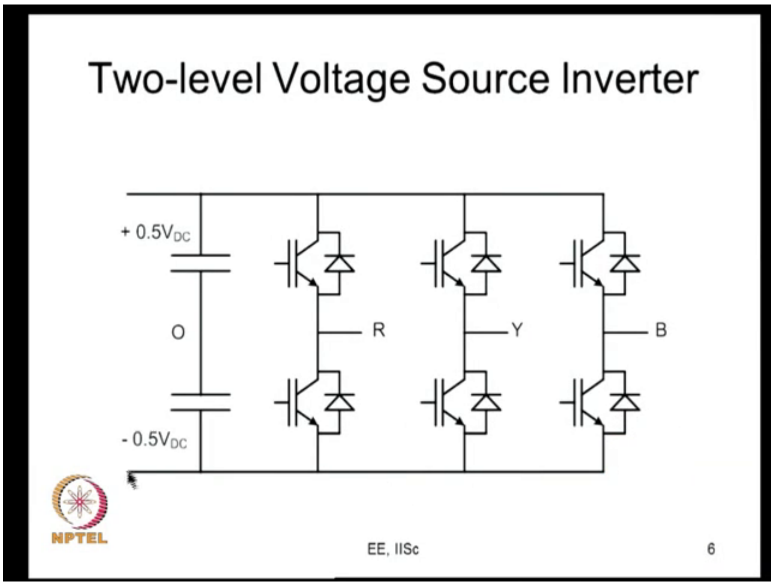

Now, let us get started this is the three phase inverter this is three-phase load which is not known I mean this is not shown here in the figure there is this dc side. And you know there are losses in these devices both the transistor and IGBT etcetera we have this now and there are conduction and there are also switching losses the present focus is really on the switching loss ok.

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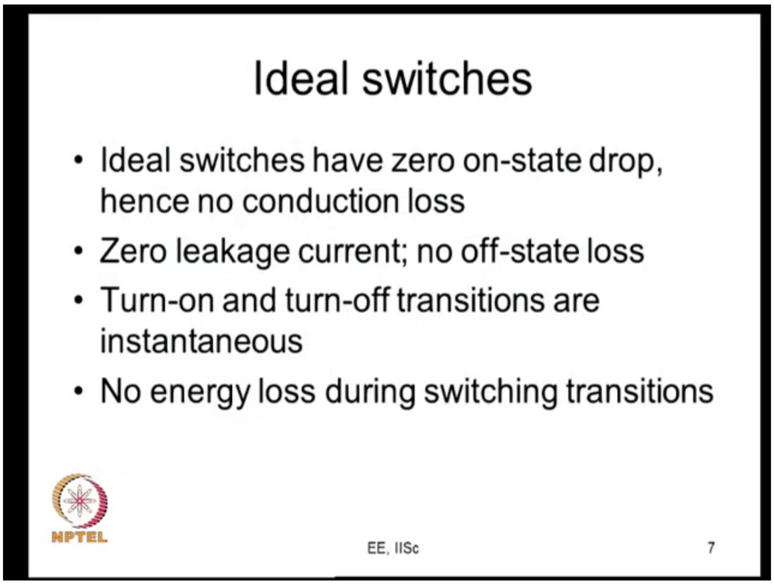

So, as we said the ideal switches will not have any forward drop and therefore, no conduction loss there is 0 leakages, current. Therefore no off state loss, and they turn on or turn off in an instantaneous fashion there is no energy loss during switching transitions that is about the ideal switches.

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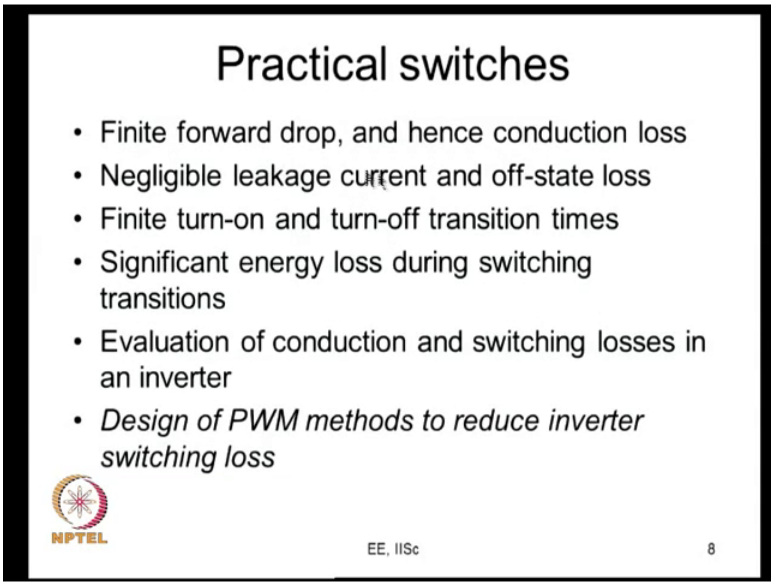

What about the practical switches? They have finite forward drop therefore there is certain amount of conduction loss and there is negligible leakage current and therefore, the off state loss is also negligible we do not have to worry about that.

So, what we need to worry about is mainly the conduction loss during the on state and the losses during the transition switching transitions, because the turn on transition and the turn off transition times are finite and there is significant amount of energy loss during these transitions.

So, we evaluate conduction loss and switching loss etcetera and we have put today we have hoping to design PWM methods, which would reduce the inverter switching loss you know significantly compared to something like sin triangle PWM or conventional space vector PWM alright.

Let us I mean I would emphasis the fact that there is reduction in switching loss not really conduction loss, but it has been shown that some of these methods result in an overall the conduction loss slightly changes may be increases or decreases but with some of this methods the reduction in switching loss is so significant that there is also reduction in the total semiconductor device loss. So, which is being discussed in some papers I mean whose reference also I will give you towards the end of this lecture.

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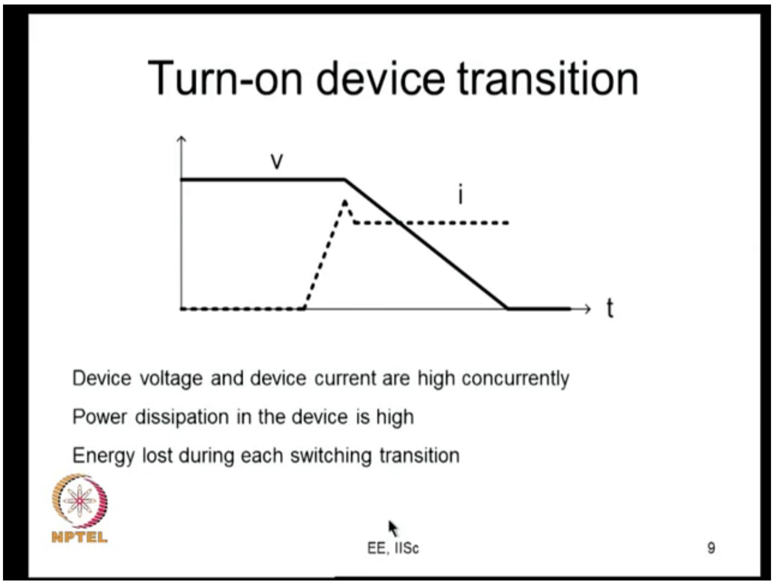

So, now why there is a loss instead I was saying you know it is not instantaneous you can see that the voltage takes so long to fall and the current takes so long to build up. Their trouble is the current builds up faster and a head of the voltage falling down.

And therefore, both voltage and current are high concurrently during this interval and therefore there is a significant amount of power loss there is power dissipation is very high. So it could be as high as the rated voltage multiplied by the rated current it could be so high I mean there is instantaneous dissipation and you need to integrate this dissipation over this interval switching interval time and that will give you the energy lost in this transition now.

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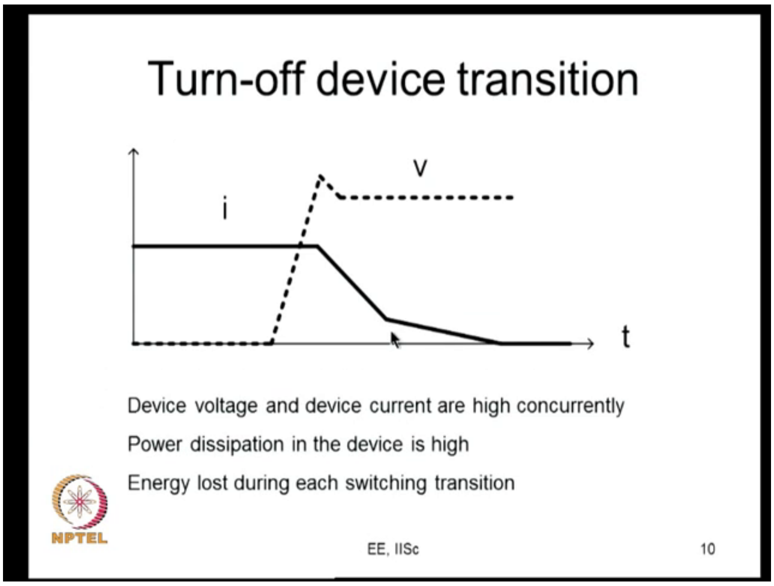

And similarly you have the a turn off transition and you know we found that the same kind of story here the current falls at before the current starts falling the voltages reason across the devices resins so there is significant amount of loss now.

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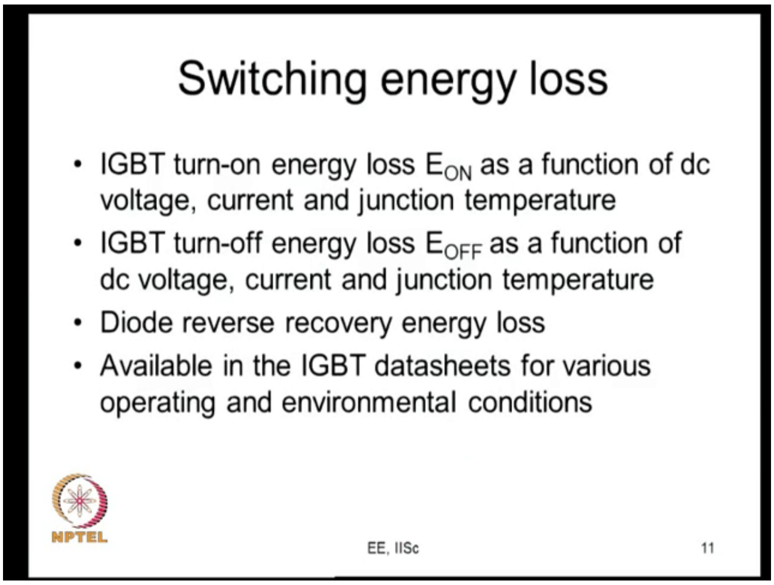

So, there is this energy loss turn on energy loss E ON, this turn off energy loss E OFF, these are available as functions of dc voltage, current and junction temperature these are normally they are available in the data sheets. Similarly the diode has what is called as reverse recovery energy loss so there is a reverse recovery process, there is some energy losses that.

So, you can find out how much is the energy loss at a particular operating condition and then you can look at how many times it is turning on and turning off. So, you will know that you know the power loss can actually be calculated, so this is largely from data sheets.

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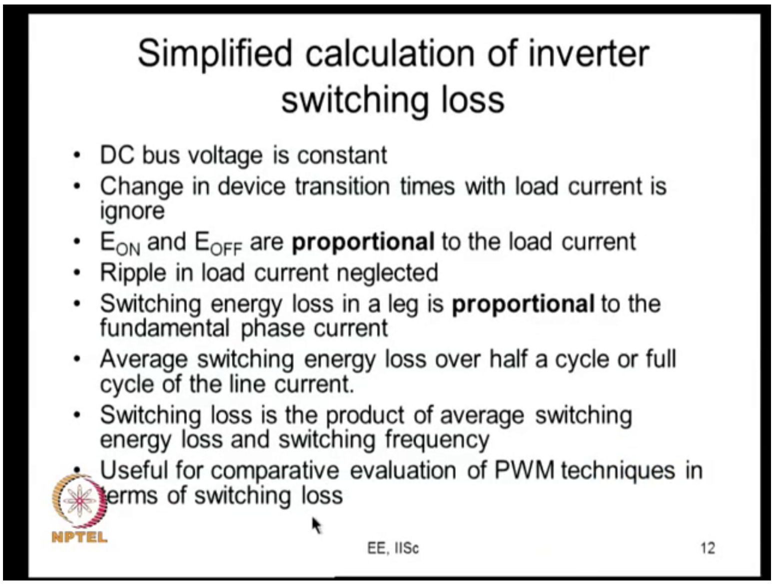

So, we also saw yesterday on some possible references where I mean in the last class where we could actually look at a few I mean there were a few papers which dealt with how you could actually evaluate E ON and E OFF. How you can actually measure the switching characteristic and actually evaluated E ON and E OFF, I am not going to repeat them today right.

So now what we trying to is that E ON and E OFF business which may be available in the data sheet or which is I mean which can be produced like experimentally you can evaluate under certain conditions we are trying to simplify that today to have a simplified analysis so that is our primary idea.

And this is also mainly for comparative evaluation of PWM methods. So, one of the assumptions is that there is this voltage source inverter, this is driving some load some or a load or a induction motor load, and I mean the over the line cycle the dc voltage cannot be expected to be constant. Because sometimes the current is higher, sometimes it is lower and the dc link current itself it keeps changing it is not a fixed current it is a time varying current and you know there is all these load side inductance and all that the d c bus voltage is not expected to be a constant realistic there will be certain amount of ripple on the d c bus voltage like 300 hertz ripple for example, because the d c bus voltage is also established by a rectifier which is supplying this inverter so you will have that.

Now, one simplifying assumption we are first doing is we are saying that the dc bus voltage is constant we are ignoring variations on that this is something which we did yesterday also. Then change in the device transition times with load current is ignored so there is when the current that is the simplifying assumption that is what happens is let us say there is R phase leg, sometimes it is switching a low current, sometime it is switching a high current in one direction and in the other direction alright.

So, when the current is low and when the current is high the device transition times are suppose to be different it is I mean you know there may be device rise time like the current, the current might take about 250 nanosecond to rise from 10 percent to 90 percent of it is final value and that may be 250 nanoseconds with some value of current, it could be 275 nanoseconds at some other value of current and may be 300 nanoseconds with some other value of current.

So, what I am trying to say is those device transitions we are first trying to ignore for the purpose of simplicity so we are ignoring those changes in device transition times with load current switched.

For example, the rise time of the device at 10 amperes and the rise time of the device at let us say 50 amperes would be different that differences being ignored. Then there is E ON and E OFF, so they depend on a number of things we are taking them to be proportional to the load current whatever is the current being switched we are say E ON and E OFF are proportional to that and this load current itself has a fundamental component and harmonic components.

So the sum of all the harmonic components is ripple we say that the harmonics are all negligible, the inverter is switching at reasonably high switching frequency and the load has good filtering characteristics. So, you know like higher frequency voltages are filtered better by inductive loads R l loads or induction motor load then we will ignore the ripple the all the harmonics of the load current.

Therefore what we have going to say is the switching energy loss is proportional to the fundamental phase current, if you want to say switching energy loss in the particular leg let us say R phase leg is proportional to their fundamental component of R phase current that is the simplifying assumption we are doing today.

Once you have that it is easy for you to evaluate so it is directly this energy loss is directly proportional to current so getting it is average value over a half cycle of the current waveform is very simple, because this E ON, E OFF and E ON plus E OFF they are also sinusoidal functions so you can very easily evaluate it is average and you can come up with the power lost so it is easy to do this now.

So, this is easy for us to do a comparative evaluation of this various PWM techniques and in terms of switching loss. So when you want to compare 2 different PWM method this simplifying assumptions make it really easy for you to do this so that will certainly be helpful for us in designing new PWM methods.

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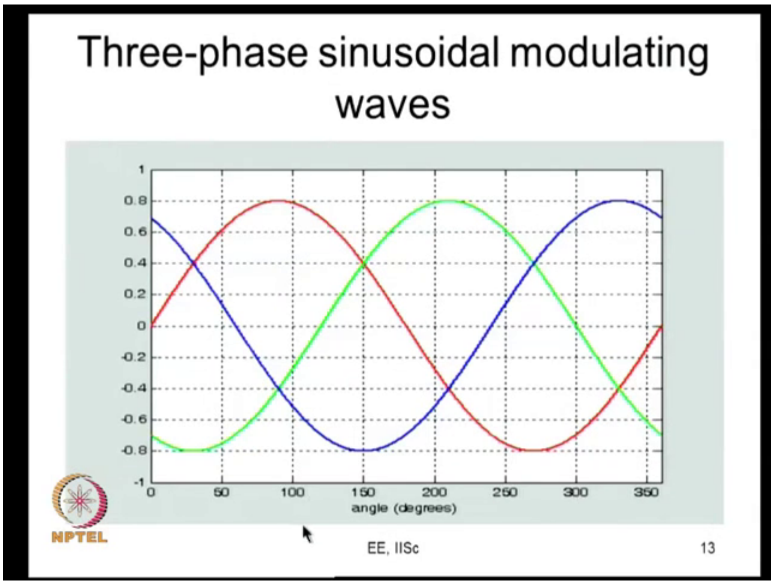

So, let us start off with our sine triangle PWM three-phase sinusoidal signals are there. So, this is for R phase, Y phase and B phase and you compare them with the high frequency triangular carrier and feed them so to the inverter.

So, what happens there is certain amount of a c voltage that is applied as I said that depends on the modulation index here it is 0.8 times the peak of the triangular carrier, the triangular carrier is not shown, but it is considered to have a positive peak of plus 1 and negative peak of minus 1 so this modulation index is 0.8.

So the peak phase fundamental voltage is 0.8 into v d c by 2, so if your v d c is 600 volts v d c by 2 is 300, 0.8 into 300 is 240 volts, so 240 volts is the fundamental phase neutral voltage applied on the load. So depending on the load impedance there will be corresponding current fundamental load impedance now.

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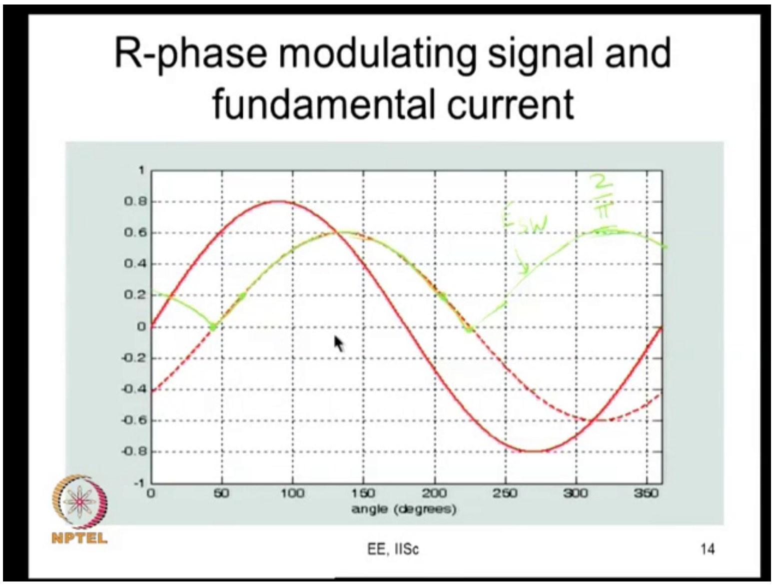

So, let us say this is the load current so there is certain amount of current and we saw that you know there is switching energy lost. Now what is our simplifying assumption we have simplified that the loss is proportional to the current that is being switched so we say that if the current being switched is 0, the loss is also 0.

So, if the current being switched is so much you know again here so let us say you know how would the variation how would this loss vary the switching energy loss it would vary in the same fashion as the current varies so let us say it is like this only. So let us say this is our switching energy loss is that the current 0 here I am sorry this is the current 0 it comes to on like this.

So, further what happens it goes up the same way like this, this is your switching energy lost, and what is it is average values it is rectified sinusoid so you can always say it is 2 by pi times it is you know peak value so it is fairly simple to evaluate the average value here now. And the significant thing that you can note down is now let us say the current wave form is having the same amplitude but a different power factor. Now the current wave form may be at a different phase angle here it is shown at 45 degree lag, it may be let us say 30 degree lag or whatever lag.

So, what is going to happen is your E S W is going to be similar to that is it is the wave shape is same as the rectified current, the fundamental current rectified it is only going to have a phase shift. But it does not matter the average value will continue to be the same, on the other hand if the current amplitude increases. For example, if the current amplitude doubles the corresponding switching energy loss peak value will also double therefore, the average loss will double.

But when the current amplitude is same is given as some 0.6 per unit here if it is same, but if the power factor changes then the whole thing is not going to change I mean the switching is not going to change. Thus, for any particular sine triangle PWM or any continuous PWM, the switching loss does not vary with power factor as we already discussed yesterday. So that is not only sine triangle PWM that is true about other PWM schemes also. Because your energy switching loss is dependent on the current that is all there is nothing otherwise it is not exactly dependent on the duty ratio, the only exemption is the duty ratio is 1 or 0. In that case a phase one switch at all, a phase does not switch at all there is no switching loss.

So, as long as the phase switches it may be 0.1 duty ratio, or 0.9 duty ratio or whatever the switching energy that is lost is proportional to the current and therefore this is the kind of wave shape that you are going to have and it is average value is going to be whatever it is. Therefore, the switching energy loss depends upon the amplitude of the load current, it is independent of the load power factor for continuous PWM methods and it does not change significantly from one continuous PWM method say sine triangle PWM to another continuous PWM methods say third harmonic injection or conventional space vector PWM method.

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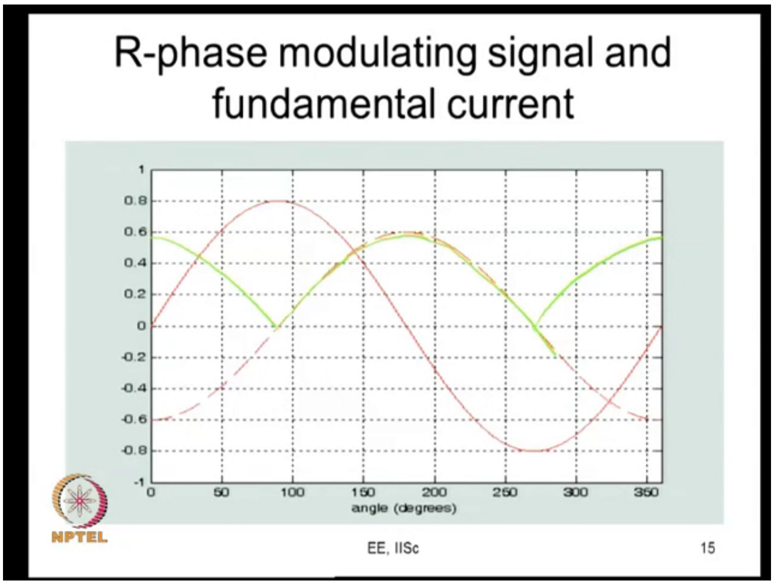

Now, you have this fundamental current now you have this one so this is the point that I was already trying to do fundamental current. And let us say this is you are I mean at a different power factor, the first is your modulating signal this is at a different power factor so you would have this here I am sorry ignore this point, so it is starts going up here so you have it like this. So, you can see that it is just a phase shifted version of what you got earlier so the average value is just the same. So, you have certain average value which would still be the same here.

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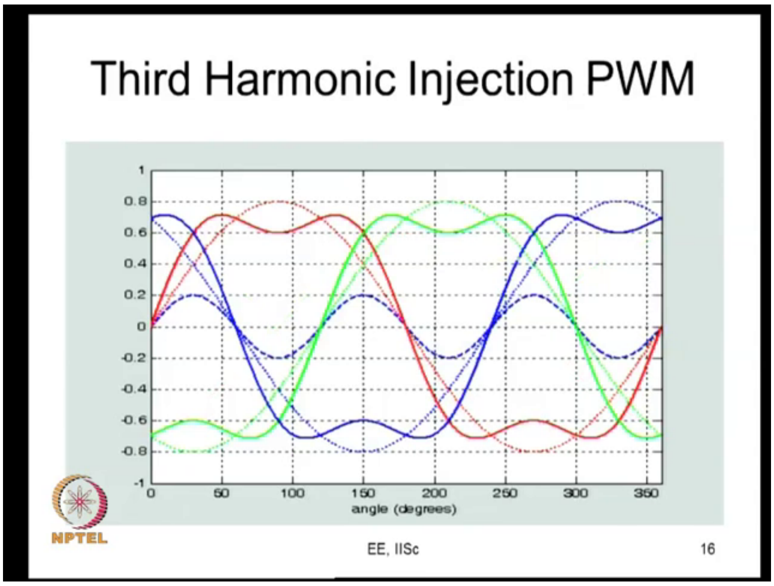

So, when this also this is an example of a third harmonic injection, so like another continuous PWM method why do you say continuous PWM method you look at the modulating signal, the modulating signals are continuous function of time or the fundamental angle so and all the phases are switching all three-phase three-phases are switching there is no phase which is clamped here alright, so the losses are same now.

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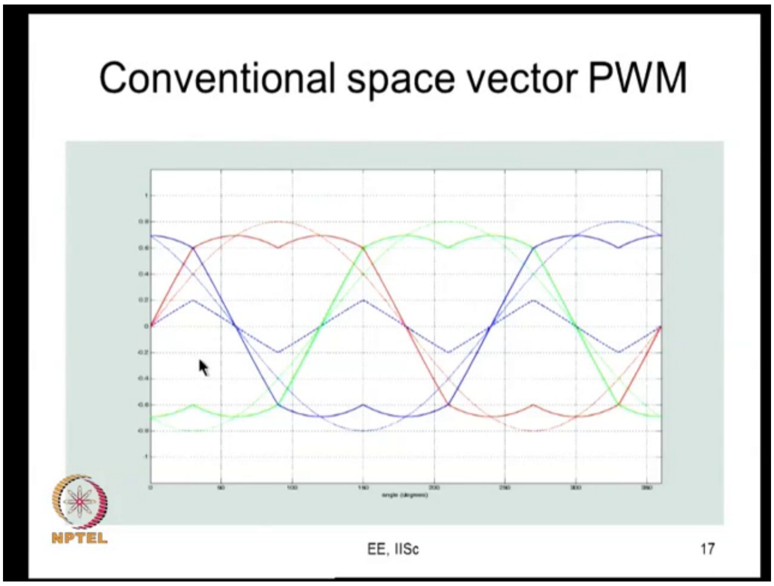

So, this is true about conventional space vector PWM also. So, in conventional space vector PWM this is your fundamental sinusoidal modulating signal. And this would be the kind of common mode added and you would get a modulating signal which is like this, it is also here also the switching loss is same as we discussed before.

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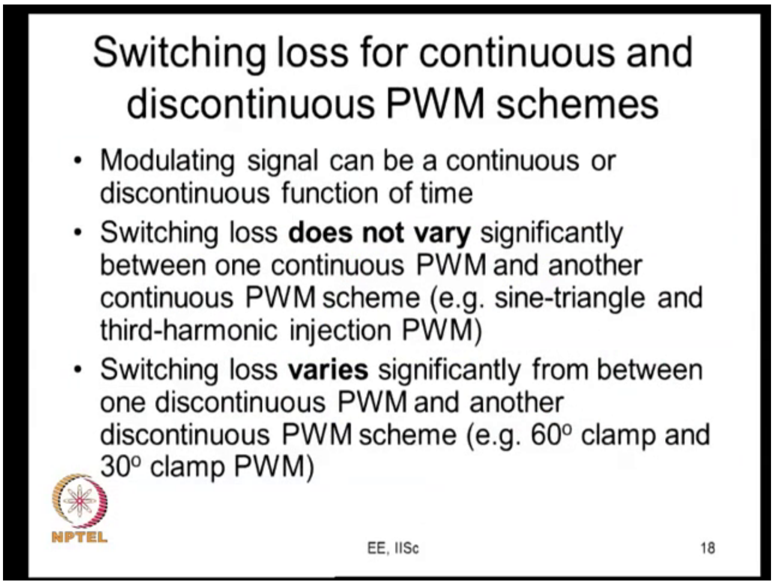

Now, just to summarize or whatever or recap can be modulating signal can be continuous or discontinuous and the switching loss does not vary significantly from one continuous to another continuous PWM scheme, whereas it very significantly from one discontinuous PWM to another as we saw some examples yesterday and so now ours whatever we want to do like designing PWM schemes. Obviously, these are not going to be continuous PWM schemes.

Because the continuous PWM schemes do not influence the switching loss at all, we are going to focus on the discontinuous PWM methods first or the bus clamping PWM methods first and then the advanced bus clamping PWM methods, next to be able to reduce the inverter switching loss that is what we going to do today.

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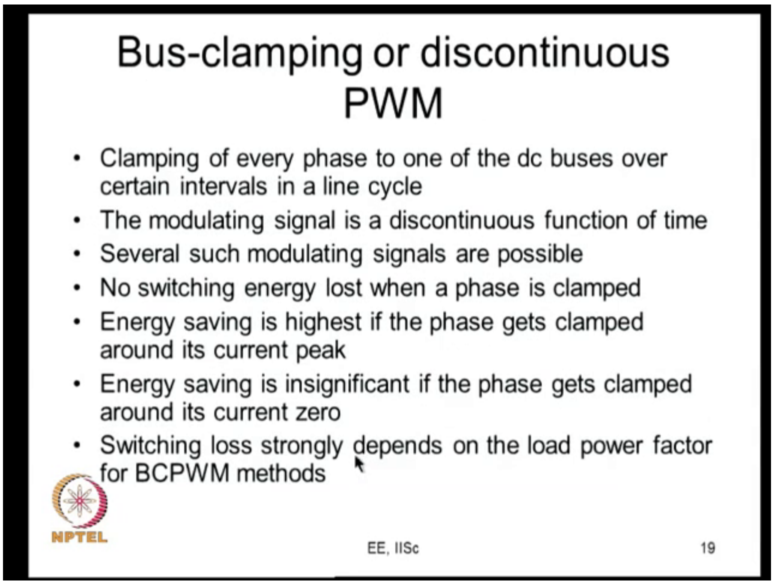

So, in bus clamping why does it affect? Because a phase is clamped one of the d c buses in certain intervals so and where it depends on the modulating signal. The modulating signal is a discontinuous function of time there are several possible modulating signals, so one modulating signal make clamp a phase between 60 to 120 degree of fundamental angle another may clamped in between 45 degree and 105 degree of that and so many different modulating signals are there. Depending on the modulating signal a phase would be clamped over some interval and another interval now. So whenever a phase is clamped there is no energy is lost so this is being one of the interesting things about bus clamping PWM and that is also one of the reasons why you know they have being studied and being used.

So, there is certain amount of energy is saved but the energy saved by not switching a phase is highest if the phase is not switched when it is current is close to the peak. On the other hand, if a particular phase current is going through 0 is very close to 0, in a particular carrier cycle and if you clamp that phase the energy saving is very insignificant.

So, these are certain things we discussed so switching loss PWM switching loss is it depends strongly on the kind of modulating signal you use, so when you are using bus clamping PWM from one PWM to another it will vary and also from one power factor to another power factor it will vary now. So, the point is now for a given power factor you will have to know what is the right kind of modulating signal that will we will minimise so that is what we need to do.

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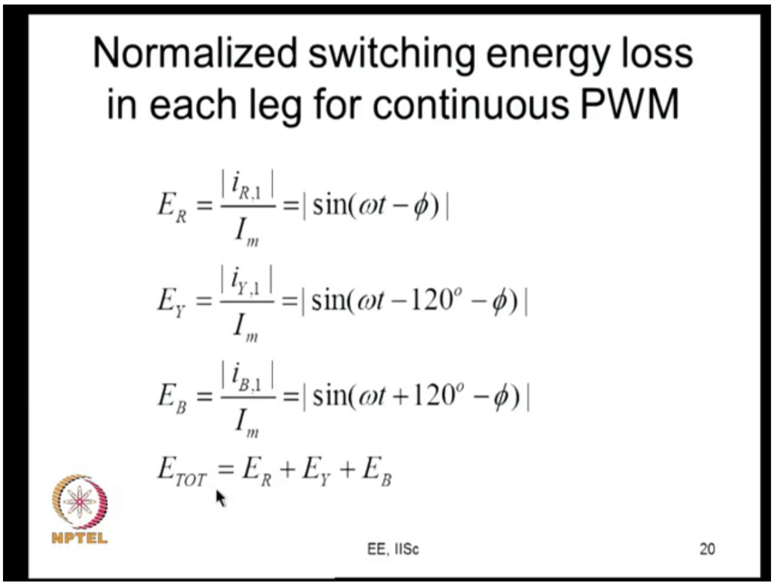

We can start looking at some examples for example we will look at unity power factors and we will see what is best and certain examples of power factor. And then we will try to go about generalizing it in some sense.

So one thing we will do is we will define certain normalised switching energy loss, our purposes is comparative study of PWM methods, so the PW all I mean we have considering a case where is a same operating condition of the inverter maybe PWM 1 or PWM 2 or PWM 3 is being used so the same operating conditions.

So, the energy loss in R phase leg we are saying that you know it is a normalised energy loss is proportional to the unsigned value of i R 1 right because it may be plus 10 ampere or minus 10 ampere the energy lost is same. So, this is i R 1 the unsigned value obsolete value of i R 1 divided by I m, where I m is the peak value of the current. And so, this is the unsigned value of sin omega T minus phi where phi is your power factor angle. So, here I have used minus phi some other places I have used plus phi but you know please do not mind that so you know what I am trying to say to this certain power factor angle this is phi here.

So, E Y. Similarly, you know you have because this is sin omega T is your R phase modulating signal, Y phase modulating signal would have like you know amplitude multiplied by sin of omega T minus 120, so the sin of omega T minus omega T minus 120 is the phase angle for the Y phase fundamental voltage. So, omega T minus 1 twenty minus phi would be the phase angle of the fundamental current of Y phase so this unsigned value of sin omega T minus 120 plus phi is the energy that is lost in the Y phase so there is approximation we have simplified today and so this is what it is now.

Again the normalised energy loss in B phase can be given by sin of omega T plus 120 minus phi it is unsigned value, so these are the losses in individual legs, the normalised switching energy losses in each leg. So, you can add up all the 3 as E R, E Y and E B.

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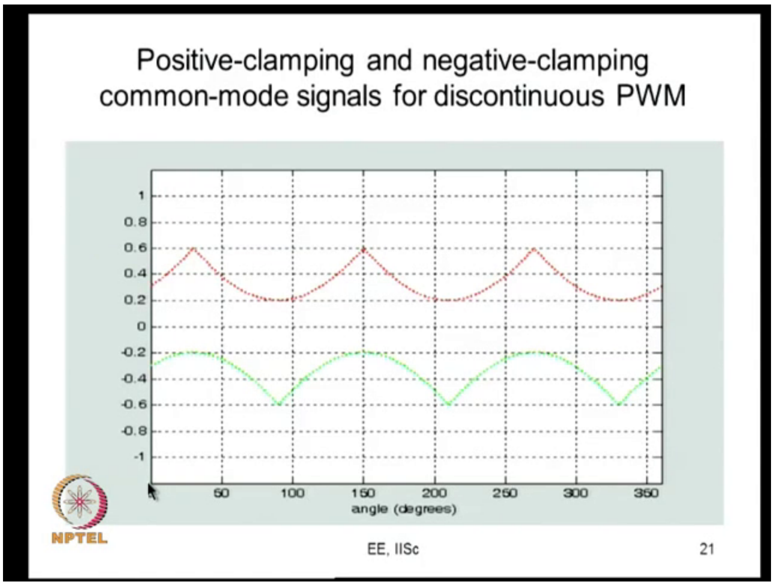

So, if you are going to discontinuous PWM why where we adding up here because all the three-phase three-phases switch in a continuous PWM. Therefore, certain amount of energy is lost in all the three. So, the total amount of energy lost is the sum of all the 3, where as we go to discontinuous PWM maybe our own switch or Y 1 switch or B 1 switch in a particular carrier cycle, so it may be E R plus E Y and EY plus E B or E B plus E R. Let us look at it now.

So, in the discontinuous PWM we are adding a common mode signal which results in bus clamping. So, there are two possible common mode signals, one we call as the positive common mode signal that is from the career positive peak, we subtract the m max the maximum one of the 3 modulating signals and we get this now.

Similarly, the carrier has a negative peak minus v peak or which is call as minus 1, the most negative of the 3 sinusoidal signals is subtracted from that and you get this what we call as the negative clamping common mode signal now. So, if you add the red one to the three-phase signals it will result in the clamping of one of the phases to the positive bus which phase that depends on which angle you are at.

Again if you add this signal to the three-phase three-phases it will result in clamping of one of the phase to the negative bus which one the phase which has the most negative fundamental voltage that will get clamped here. So, what we do is we follow this for 60 degrees and follow this for another 60 degrees and is we do it in an alternative fashion as we discussed this before.

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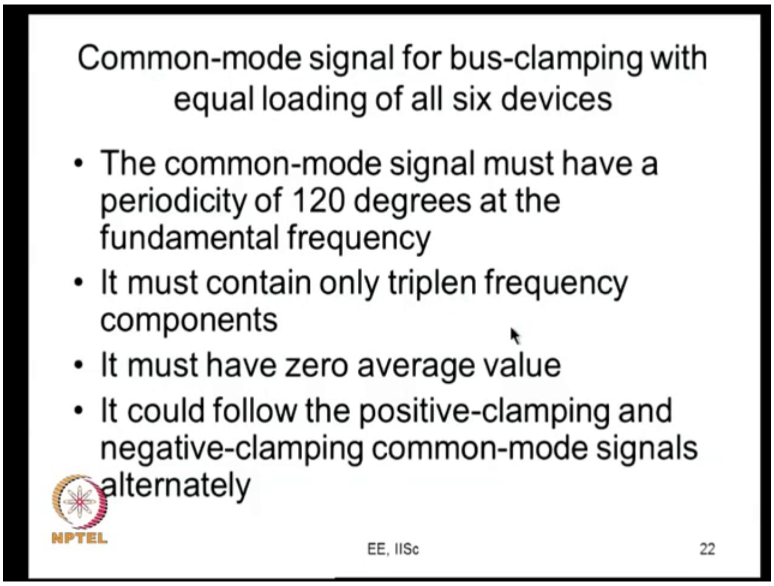

And if you follow these conditions we can make sure that we can ensure bus clamping with equal loading or with you know power dissipation in all the 6 devices being equal. So, if you are operating an inverter you have to make sure that the same amount of power is being dissipated in all the 3 legs, and even in each leg the top device and the bottom device should also have the same amount of power dissipation that can be ensured if you go through all these things and particularly that it must have zero average value and so you can do this now. So, subject to these conditions many bus clamping PWM methods are possible.

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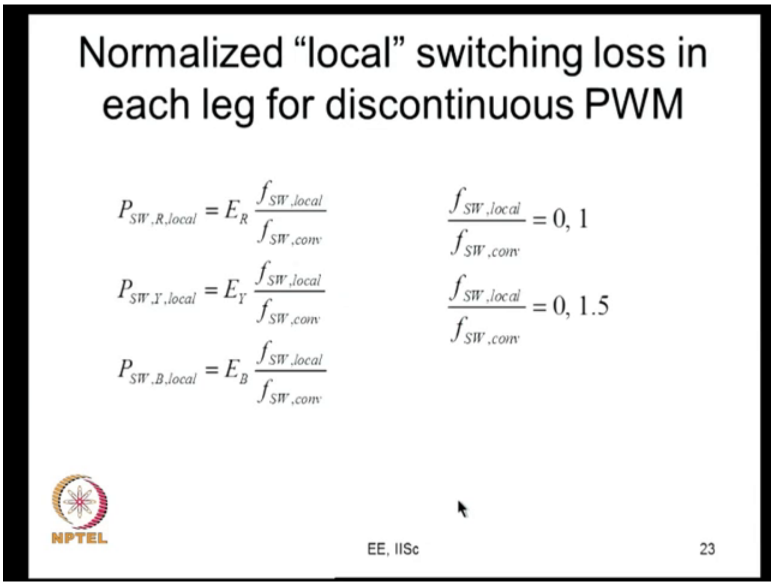

So, what happens in bus clamping PWM if you look at R phase you will have an R phase switching energy loss which normalized R phase switching energy loss as we derived and discussed before this is simply proportional to i R.

Similarly this is a Y phase switching energy loss, this is B switching energy loss, but whether the phase switches or not is a question. So, what we can actually do is multiply this by what we call as a local switching frequency that is it may be switching or it may not be switching and that local switching frequencies again normalized with respect to the switching frequency of the conventional space vector PWM or a sine triangle PWM equivalently.

So, this is energy this is normalized energy we are multiplying by you know switching by a frequency to get power of course all of them are normalised here now. So, the same way E Y can be multiplied by the same factor to get what you call as the switching loss this is the power loss in the Y phase leg and this is local. What you mean by local is this will vary with omega T as omega T varies this number will vary, because obviously this varies and maybe this also would vary.

Similarly, E B can be multiplied by this normalised switching frequency; normalised switching energy loss multiplied by normalised switching frequency to get the normalised power loss. Now what about this ratio when you are using a carrier frequency which is same as the conventional space vector PWM and a phase is switching then f S W by f s local is equal to 1, but the phase may not switch always the phase may be clamped. If the phase is clamped then f S W local is 0, f S W local by f S W conventional is 0, so there is no power loss in that.

For example, if R phase is clamped then there is no power loss, so here P SW R local will be 0, Y and B may be switching at the same carrier frequency as fundamentally then these will actually become this is E Y and this is EB essentially multiplied by 1.

Now so this is when it is clamped and when it is not clamped it should be 1 now, now what it is 1.5 so what happens with bus clamping PWM is the average switching frequency is different from the carrier frequency. Let us say the carrier frequency is 3 kilo hertz what does a typical bus clamping PWM do it clamps a phase for 60 degrees in the positive half cycle and 60 degrees in the negative half cycle.

So, the device does not switch 300 cycles in a second it does not switch all 300 cycles, so the carrier goes through the 300 cycles in a second individual devices do not switch. How many cycles do they switch in a second? It is only 2000. So, this switching frequency, but the switching frequency is not uniform everywhere it is sometimes 3 kilo hertz and sometimes it is 0.

So, the switching frequency of a particular device if you look at is 3 kilo hertz for 120 degree duration in a half cycle and 60 degree in another one. So, we can call the term average switching frequency, the average switching frequency is only 2 kilo hertz. Now, the device is actually switch only 2000 times in a second though the carrier frequency is 3 kilo hertz.

So, the average switching frequency is low so what happens the switching frequency is reduced switching loss is also reduced, but sometimes the harmonic distortion might be affected. So, it is you know so sometimes what we do is to really increase the carrier frequency to 1.5 times, if you increase the carrier frequency to 1.5 times.

Now let us say conventional is switched at 3 kilo hertz, where as we are considering a bus clamping PWM which is switched at 4.5 kilo hertz carrier frequency. Then the average switching frequency with d c PWM will be equal to 3 kilo hertz so sometimes it is fair to compare both of them at the same you know average switching frequency which is the exact number of switching cycles every device switches in a line cycle or a second ok.

So, actually if you increase the carrier frequency like this then what you are doing is your device is switching at the same average switching frequency, but you will be able to achieve better harmonic distortion, lower harmonic distortion at high modulation indices. This is also fact which we have studied and it is being widely reported in the literature, we also saw a few papers you know reference which talk about this.

So, what we do is sometimes we use the same carrier frequency as the conventional or sometimes we use a higher carrier frequency that is 1.5 times that of the conventional. And therefore this FSW local will be either 1 or 1.5 depending on what the carrier frequency we have chosen is when the phase is switching, and when the phase is clamped it is only going to be 0. So, this way you can evaluate the normalised local switching loss for each leg for R phase leg and Y phase leg and the B phase leg.

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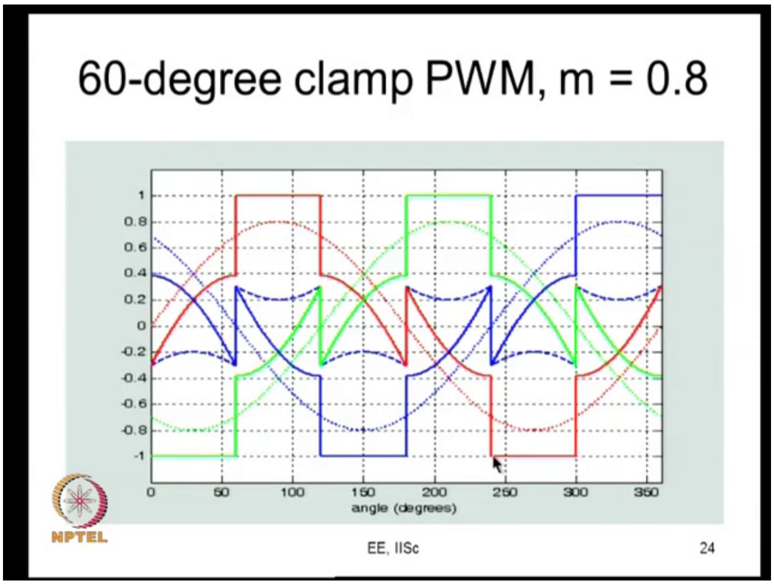

So, now let us say take this specific example of 60 degree clamp so it is clamped for 60 degrees in the middle of every half cycle and that is why we call it 60 degree clamp

PWM it is a nomenclature you know some many papers might actually call it d PWM 1 for example. So, this is the sinusoidal R phase sinusoidal signal. And this is the common mode signal and the common mode signal is been added and only you get this one now so R phase is clamped here and the R phase is also clamped here now.

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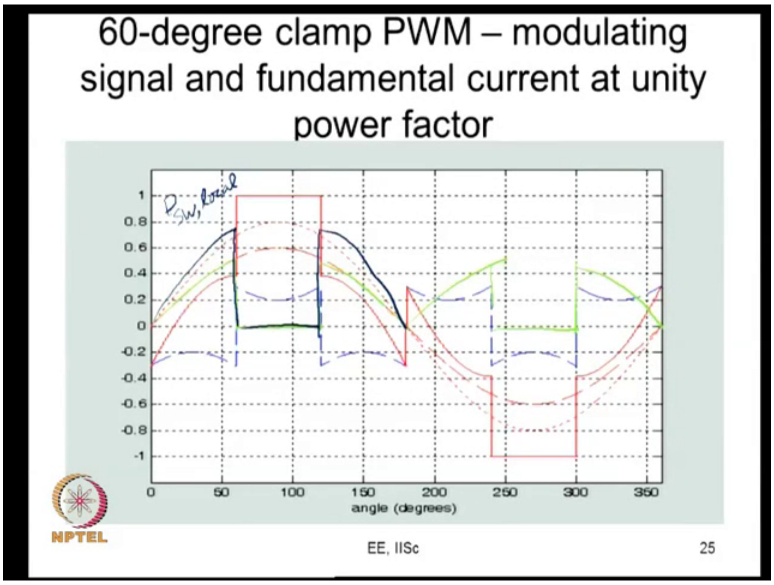

So, if let us say we are talking of unity power factor I have reproduced just the R phase fundamental modulating signal this is the R phase actual modulating signal and this is the common mode component, this is the current. Now what I have done is I have reproduced the current I mean there is no fundamental current here. So, if this is the fundamental current what is the loss going to be the switching energy loss we have said is proportional to the current so we can say that this is the switching energy loss, this is the switching energy that has been lost.

Now, here what happens this is how the switching energy lost is it follows here this is in one half cycle. How about the middle duration the switching energy lost is 0, because the phase is not actually switching at all so you have the switching energy loss like this. How about that the same thing you will have in the other side also the switching energy loss here will be 0 and it will go like this it will come down then here again will go back to 0, this is how the switching energy loss will be. If you are considering the same carrier frequency as the fundamental then what happens you actually save 50 percent of the switching loss.

Now, what you might actually be doing is this is the local switching loss now if I consider the carrier frequency to be the same as the conventional if the carrier frequency. Let us say is 1.5 times of the conventional what will happen is this thing will get multiplied by 1.5.

So, what is the number here this is something like you know actually it is 0.6, this is 0.6 sin 60, 0.6 into 0.866 something little higher than 0.5 so this will roughly go to 0.75. So this would be the P S W local this would be the P SW local for R phase at a higher carrier frequency so this will come down like this so alright.

So, what has happened between here and here there is a difference now here it increases by 1 and half times why because it is being switched at a higher carrier frequency, here it is also at higher carrier frequency here also. If you look at the average switching loss you average this PSW local over a half cycle you a going to get the actual what the switching loss you will see that the switching loss is still about 33 percent lower than the original switching loss that you will have with the conventional space vector PWM.

So, this is the best way of clamping if you are having unity power factor load the current also has it is peak whenever the voltage has it is peak. So, the best thing whatever you want to do is to clamp the phase around the peak of the current which is same as clamping the phase around the peak of the voltage and that is precisely what you are doing. So, 60 degree clamp PWM is the ideal answer to reducing switching loss when you are at unity power factor, when your load is at unity power factor. The problem is when the load is not at unity power factor what happens you need to change it a little bit.

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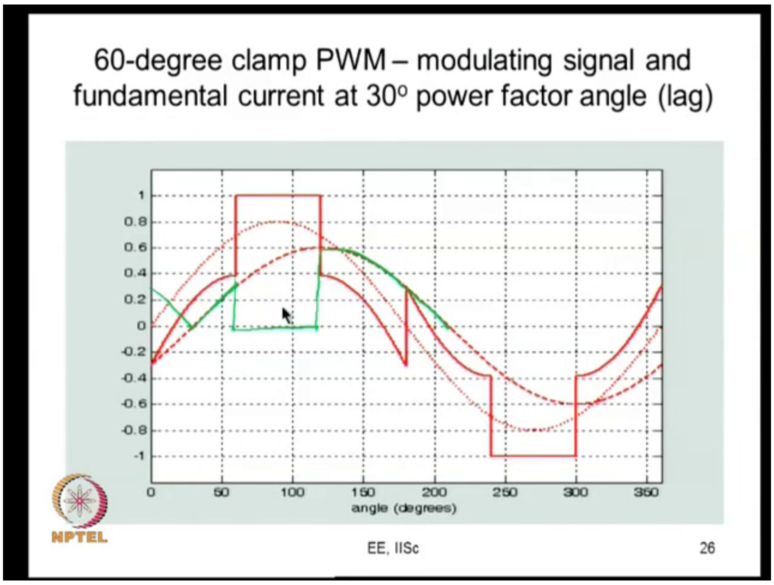

There is another particular case we are taking now so in this case if you see a phase is getting clamped. But where is the current? The current is actually little lower and here so here the current is high it might have been advantageous if the phase could have been clamped here but the 60 degree clamp PWM is not really clamping like that.

So, if I were to draw the energy loss here so this might be 0 here, this would be 0, this is the current waveform it follows here and it goes higher. So, you can see that it is not quite there is your reduction, but the reduction is not exactly at the middle. So, the reduction in the energy lost is lower than what it was for the 0 degree power factor angle case.

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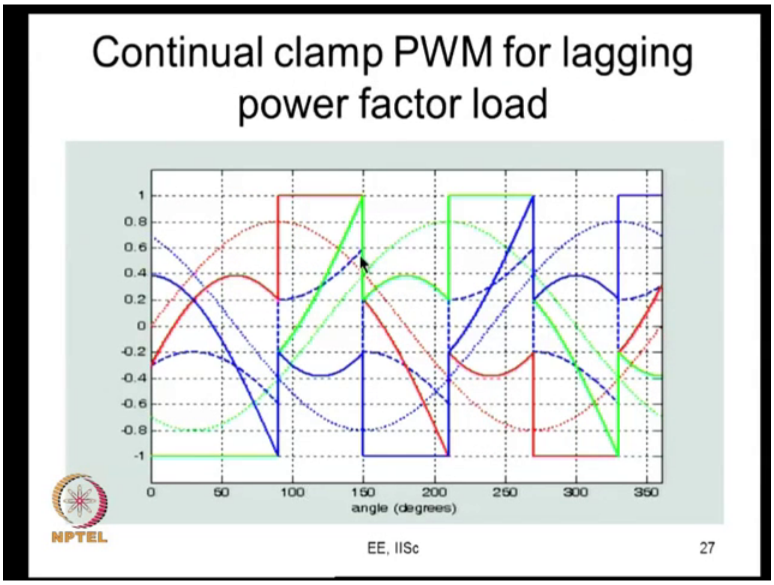

So, what should we actually do it is best that you clamp it around this where is it coming now 120 degrees is where the peak is occurring better clamp the phase between 90 to 150 degree which is what you are doing here clamping here from 90 to 150 with this PWM method you will get the same advantage to the same extent that you got with 60 degree clamp PWM at unity power factor. So, what you have done you are clamped in between 90 to 150 degree when the phase current is at we know the peak is here.

So, the next slide I have shown you know this is for the leading power factor and that is the lagging power factor, so if it is like here so this is about 90 to 150 degree you are going to clamp it around this now.

So, if let us say it is not 30 degree lag the phases is lagging current is lagging by 20 degree lag. So, what you can actually do is you can clamp from 80 degree to 140 degrees so from up to 0 to 30 degree possible you can actually shift your clamping position so that you can get a fifty percent reduction in the energy lost. If you are talking of reduction in switching loss if you are talking of the same frequency and 33 percent reduction if you are talking of in increased switching frequency of 1.5 times. So, this is what is possible now this is for 30 degree lagging power factor case.

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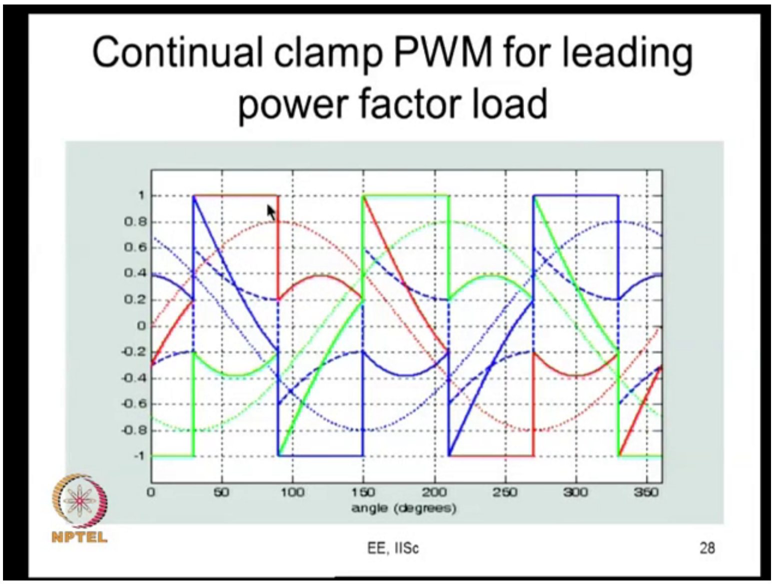

If you are talking of 30 degree leading power factor case sometimes load could be leading power factor in that case this is helpful. So, if the load current is 30 degree leading power factor then this would actually result in the best possible reduction that is possible with this now. So, we are looking at everything in terms of the modulating signals right now after while we will go into the space vector domain and we will do it a little differently.

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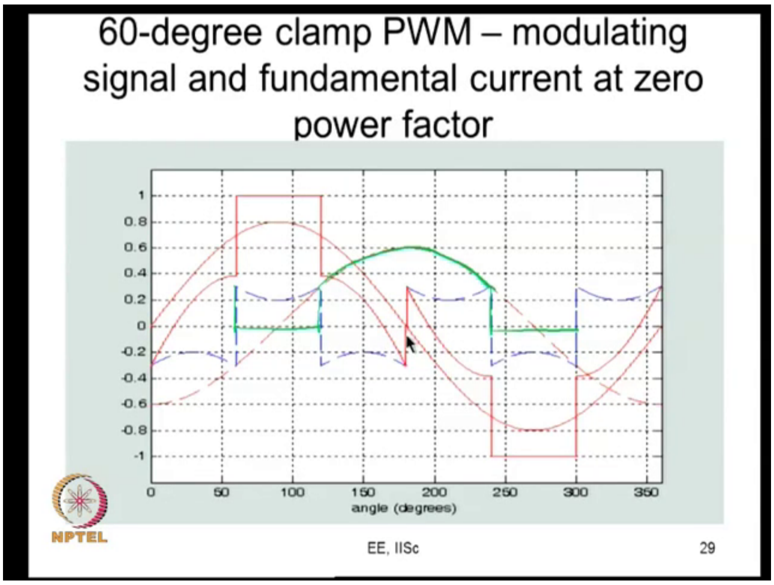

So, now let us say you come to the 0 power factor we are looking at very very specific examples for example, we have looking at unity power factor we are looking at 30 degrees. And we are looking at 90 degrees kind of power factor angle so that we are developing some idea.

Now, let us say it is 0 power factor so the current is actually crossing 0 when the voltage is at it is peak and the phase is clamped here so it is useless I mean the amount of energy that you have going to save anyway even if you had switched the phase the current going through 0, the energy loss is very slow so you do not need to do this now.

If you know you look at the energy loss how is the energy loss, it is saved here. Otherwise the energy loss follows here. So, here also the energy lost is 0, the energy loss follows like this. So, you can see that the energy loss is quite high you are not clamping the phase when the current through the phase are the energy switching energy loss is high, so this is not the right thing to do. So, it will result in very small reduction in your switching loss when you average it over a cycle.

In fact, if you consider this is only if you consider the same carrier frequency if you consider the carrier frequency it will be 1.5 times, then you will see that 60 degree clamp PWM actually results in higher switching loss actually higher switching loss than conventional space vector PWM at 0 power factor. So, this is a very good solution when it is at unity power factor, but this is not a good solution when you are really talking of 0 power factor you need to go do it differently.

So, let us say 0 power factor what happens it trouble with this low power factor is when the current is having it is peak the voltages close to 0 and a phase cannot be clamped. So, the current phase carrying the highest current cannot be claimed, but you should be able to clamp the phase carrying the second highest current we just what is achieved by split clamp PWM.

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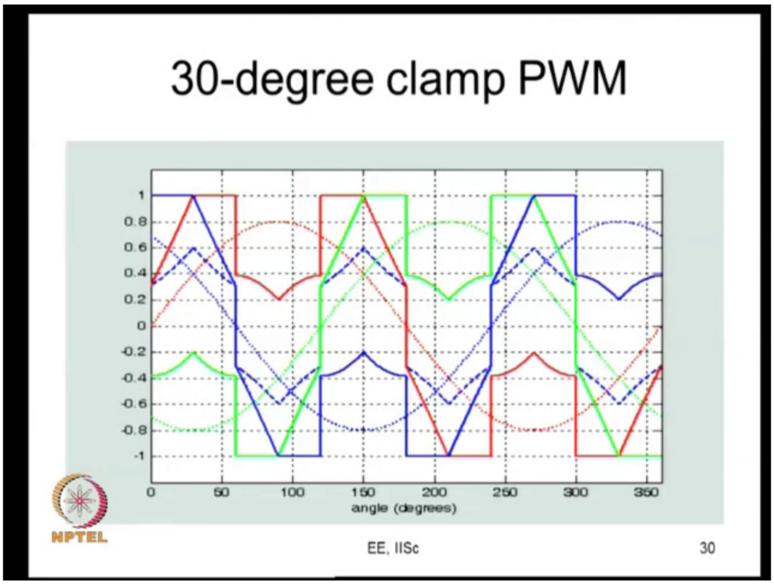

For the same example, let us say you take 30 degree clamp PWM; now what this 30 degree clamp PWM does is, it clamps here like from 120 to 150 degree the R phase is clamped. So, it is 0 power factor load so you will see that here it is 0 crossing at 120 degrees it will be 0.5 times the peak value, here it will be 0.866 times the peak value, so it will actually be clamping the current when the current is between 0.5 times it is peak and 0.866 times it is peak.

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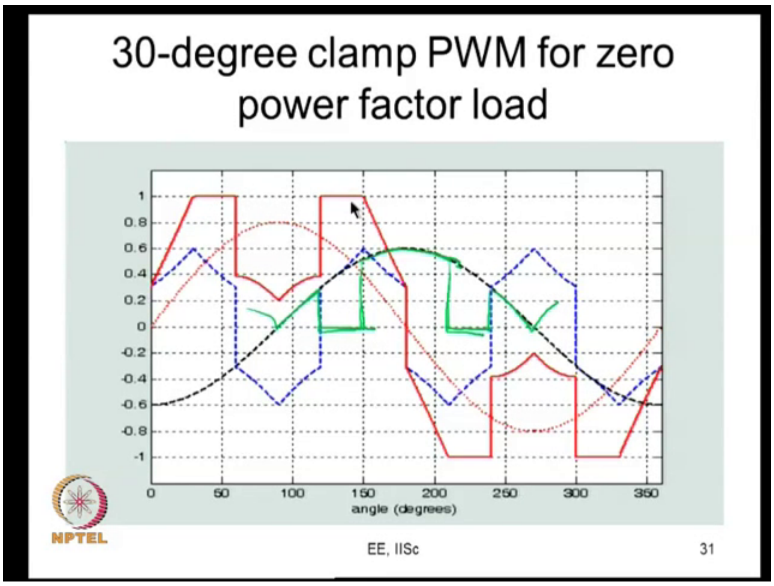

So, I have found it more clearly here. So this is for example, is the R phase modulating signal for 30 degree clamp PWM it is R phase modulating signal this is the common mode component for the 30 degree clamp PWM you add that then you get your R phase signal like this.

Now what you are doing this is your R phase fundamental current you can see that it is switched here when the current is between 0 to 30 degrees it is fine you cannot clamp it when it is close to it is peak, because the voltage is close to 0. So, you are doing the best thing you are clamping this phase when the current is between 0.5 times the peak to 0.866 times the peak. Let me draw this energy loss.

So if I draw the energy loss here it follows the current up to what point up to this point then it is 0, then up to here it is 0, then here it goes so here so this is 1 half cycle of the energy loss, this is 1 half cycle of the energy loss. So, you see that it starts increasing this side again from here to here if you see you cannot clamp close to the peak so you are clamping it between if you call this as 0 you are clamping between 30 to 60 degree and 120 to 150 degrees you cannot ideally you want to clamp between 60 to 120 it is not possible at all so you are doing this now.

So, this 30 degree clamp PWM is a particular example of split clamp PWM, so this clamping duration and that clamping duration add to 60 degree it is 30 and 30 here it need not have to be it can be 10 and 50 here or it can be 50 and 10 here for example so that is what we call as split clamp PWM.

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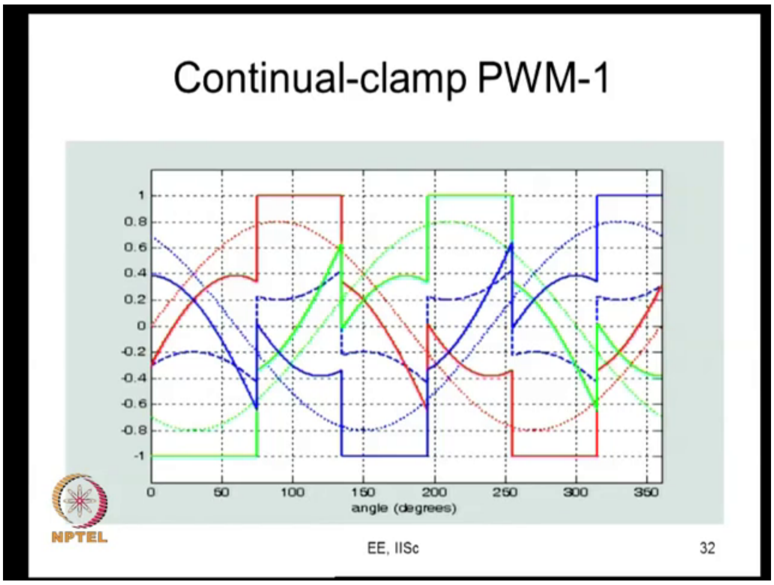

Now we will generalize this now this is continuous clamp PWM. So, what you do you can clamp a phase for 60 degrees continuously. So, to a particular bus here again the same phase is clamped to the other bus for 60 degrees continually. Therefore you call it continual clamp PWM. So, this is oriented towards lagging power factor loads so I am calling it as Continual-clamp PWM-1.

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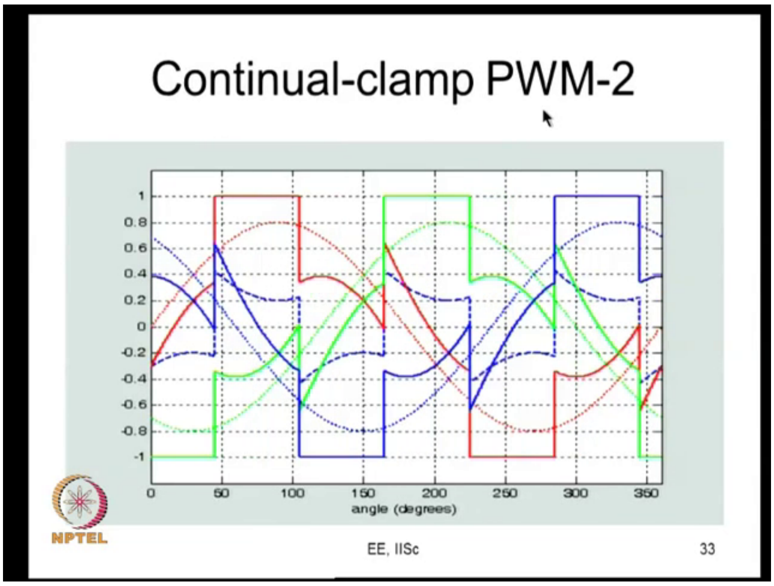

This is oriented towards leading power factor loads and which calling it as Continual-clamp PWM-2.

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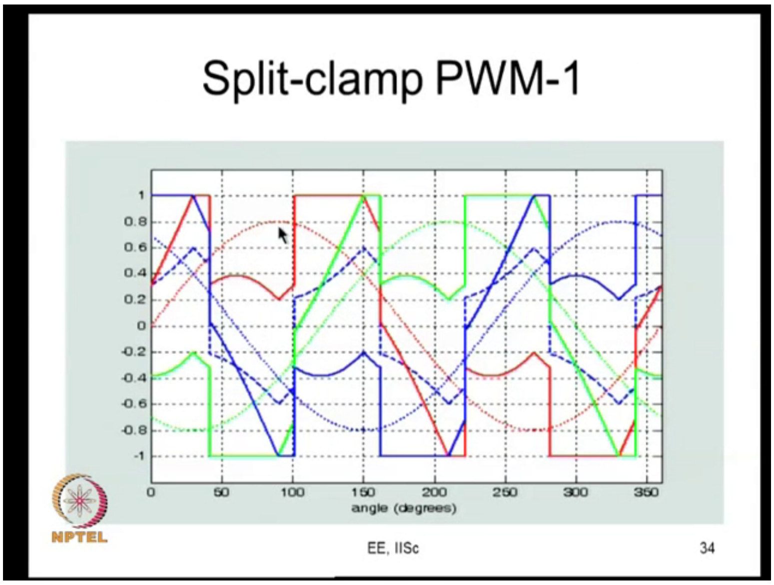

So, then we have split clamp PWM so here we have this split clamp right. So, here you have this is low and this is high like say a 10 degrees I mean this is 50 degrees.

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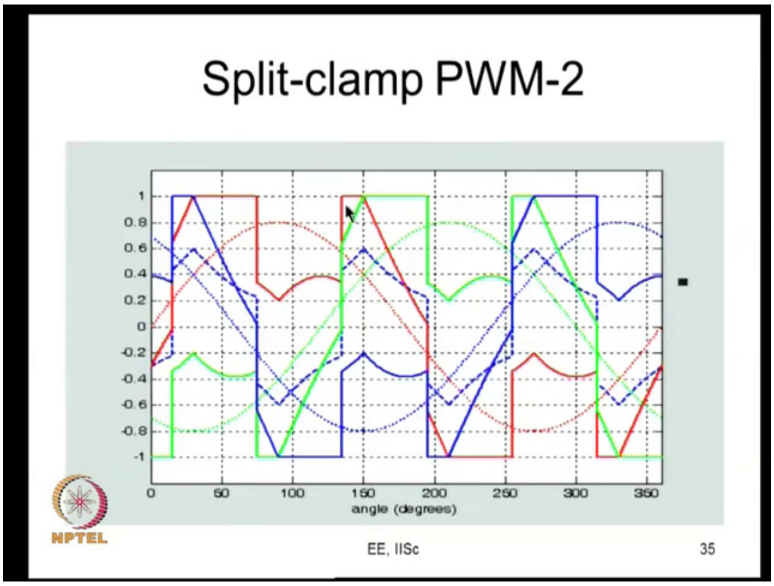

The other example is this is 50 and this can be 10 we call this split clamp PWM 2, so this continual clamp PWM and split clamp PWM together represent the complete range of bus clamping PWM methods except 120 degree clamp. So, these are the PWM methods which can ensure that all the 6 devices the converter operates in a balanced fashion so this actually summarises everything.

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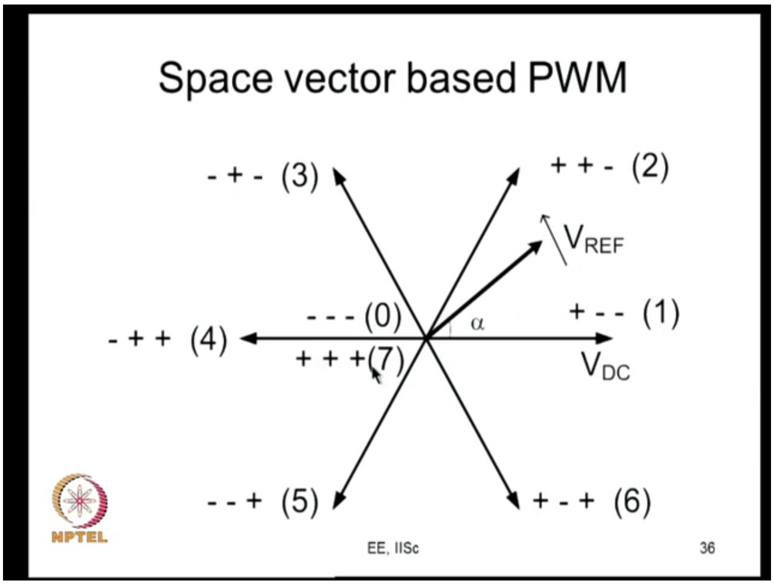

Now let us look at the same thing from the space vector point of view how do you represent. So this is a space vector domain reference vector is rotating you have a particular sample. Now that sample is obtained by time averaging of this vector this vector and that vector.

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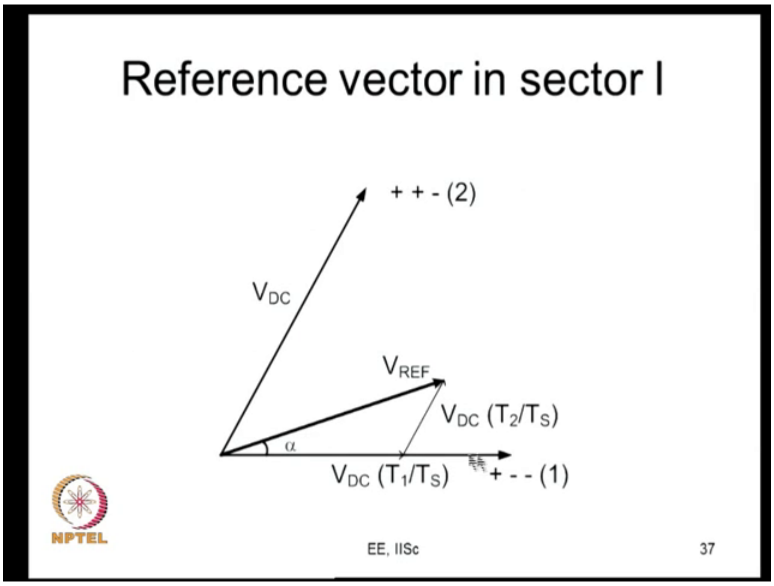

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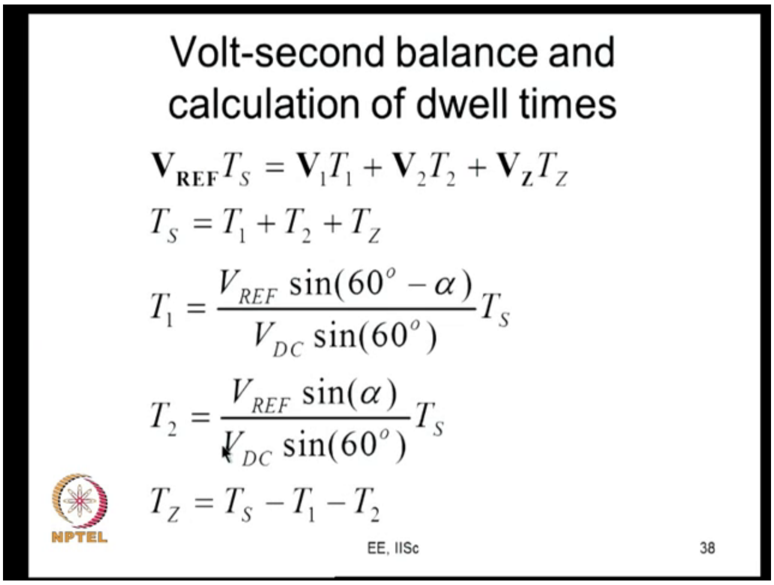

Now, we are calculating all the dwell times like this we have discussed this I mean many times when we did this space vector based PWM module, and the subsequent line current ripple modules.

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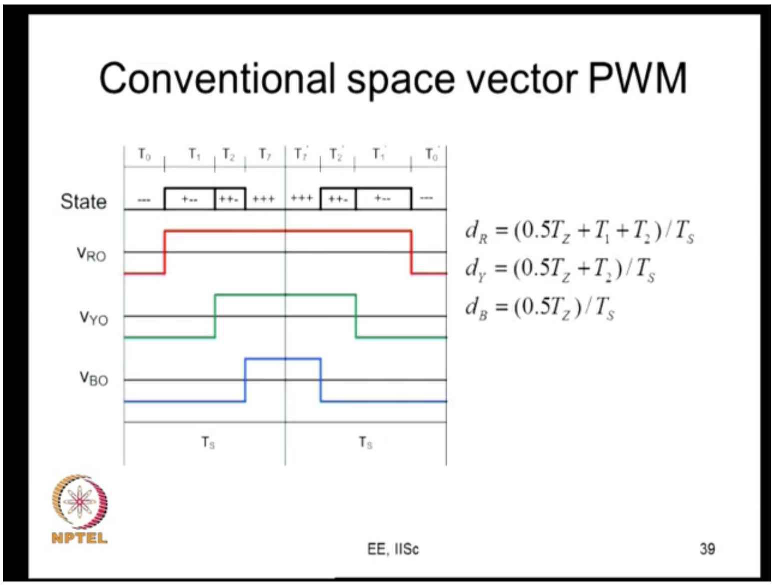

So, we are going to apply the vector states like 0, 1, 2, 7, 2, 7, 2, 1, 0 like this when you a space vector PWM the active vector is are applied for a T 1, T 2 seconds, the null vector is applied for T z by 2 and T z by 2 here if it is conventional space vector or it can be some other ratio for the other continuous PWM methods and the duty ratios are actually given by this now.

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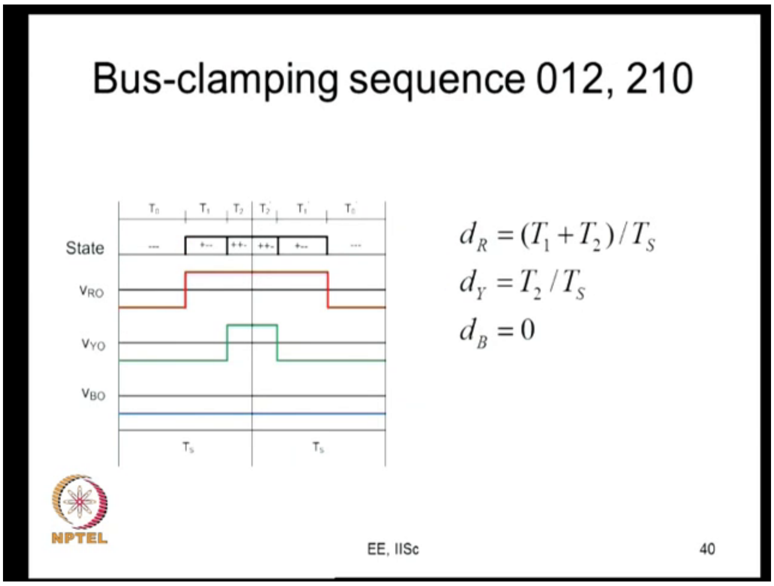

If it is bus clamping PWM method what do you do? You apply let us only 0 for the entire duration T z or you know 0, 1, 2, 2, 1, 0 so this is one way of doing bus clamping PWM.

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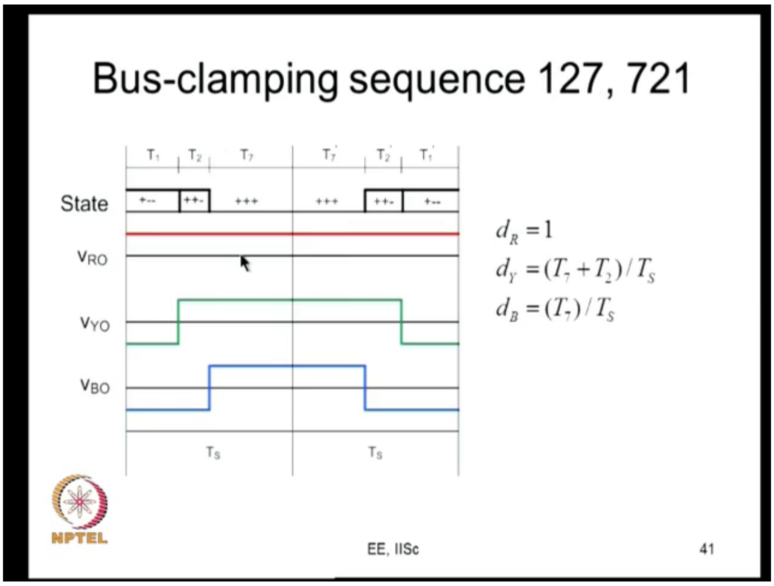

This is the other way of doing bus clamping PWM, you apply only the 0 state 7 the entire T z you apply this 0 state 7 so 0 never gets separate in this case R phase gets clamped in the previous case the B phase was getting clamped to the negative bus here R phase is getting clamped to the positive bus. So, these are the only two possible switching sequences that are bus-clamping sequences in sector 1.

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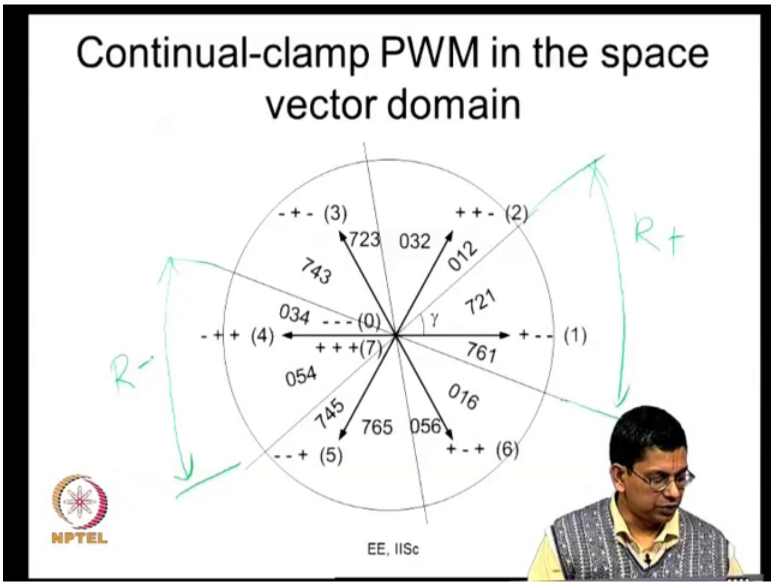

So, you have to only either apply one sequences or the other. So, what you do is let us say sector one, you divide that arbitrarily by some angle gamma; gamma can be vary anywhere between 0 to 60 degree between 0 to gamma let us say you apply 7 2 1, 1 2 7 sequences between gamma to 60 minus gamma you apply 012, 210 sequences this is one possibility.

You can apply the similar sequences in other places for example, 721 is similar to 032. So 721 in sector 1, this is 032 in sector 2 you can apply similar sequences everywhere now. If you apply these sequences what really happens is you can see that R phase is clamped over this duration, you can see that R phase is clamped over this duration and similarly you will also find that R phase is clamped, but to the negative bus during this duration. So, this is same as your continual clamp PWM method.

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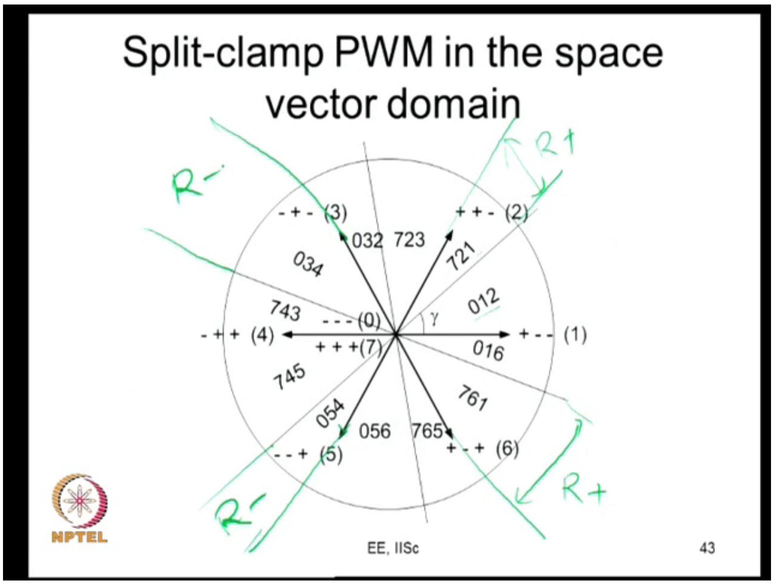

Similarly you will find with the other phases now let us say this is the other option. So, you are using 012 in the first portion of sector one and 7 2 1 in the next portion of sector one.

So, if you look at this what you will find is you will find that R phase is clamped to the positive bus in this duration and again you will find that R phase is clamped to the positive bus in this duration. So, R phase is clamped for a total of 60 degrees, but it is divided here this is for a duration gamma and this is for a duration 60 minus gamma in these two it is divided like that.

Similarly you will also find that R phase is clamped to the negative bus opposite here this will be R clamped to the R phase would be clamped to the negative bus here also R phase is clamped to the negative. So, this is split clamp PWM represented in the space vector domain so these are this is continual clamp PWM this is split clamp PWM this is how they are representing between them you know together they represent all the discontinuous PWM methods except like 120 degree clamp PWM which are asymmetric anyway.

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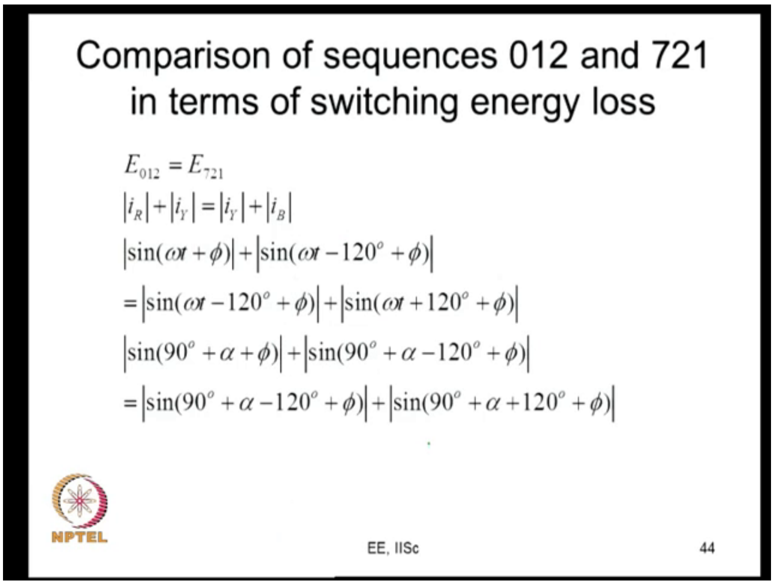

Now, how if you want to compare two sequences you can only apply 0 1 2 or 7 2 1 you know those are the two sequences. Basically how do you compare you compare them based on the energy lost how is a energy lost the total energy lost in a sub cycle with 0 1 2 and 7 2 1. How much is the energy lost here? I am talking about normalised energy lost so this E 0 1 2 is actually given by the unsigned value of i R plus i Y and this loss if you are applying 7 2 1 you are switching Y phase and B phase you are not switching R phase so the loss is given by unsigned value of i Y plus unsigned value of i B. Now what is unsigned value of i R it is sin of omega T plus phi, I am taking this phi as the power factor angle if phi is negative you can call it lagging power factor, if phi is positive you can call it as you know leading power factor alright. So, this is i r, this is i y, the power factor angle is phi and this is i Y, this is i B I have written this so I have written the same thing as sinusoidal functions.

So, what is this omega t I am considering sector one. So, sector one starts from where the R phase is having a positive peak omega t is equal to 0 at the positive 0 crossing of R sector one starts where are is having a positive peak. So, omega T equals 90 degrees where R phase starts and it is 90 plus alpha omega t can be represented as 90 plus alpha sector one extents from 90 degree to 150 degree so this is 90 plus alpha where alpha ranges 0 to 60 degree I have not indicated that, but you can certainly understand the range of alpha is 0 to 60 degree.

So, you can write this expression now so you have an equation you solve this equation you will get a relationship between alpha and phi for which the energy the losses are equal you can get the condition E 0 1 2 less than E 7 2 1 or you can get the condition E 0 1 2 greater than E 7 2 1. So, you would know for what values of alpha and phi for a particular value of phi what ranges of alpha 0 1 2 is better and 7 2 1 is better this is one way of doing this is the basis by which you can arrive at a particular PWM method which will result in the lowest switching loss at a particular you know this is discontinuous PWM method for a particular power factor angle. So, this can help you this so you can compare these two sequences now.

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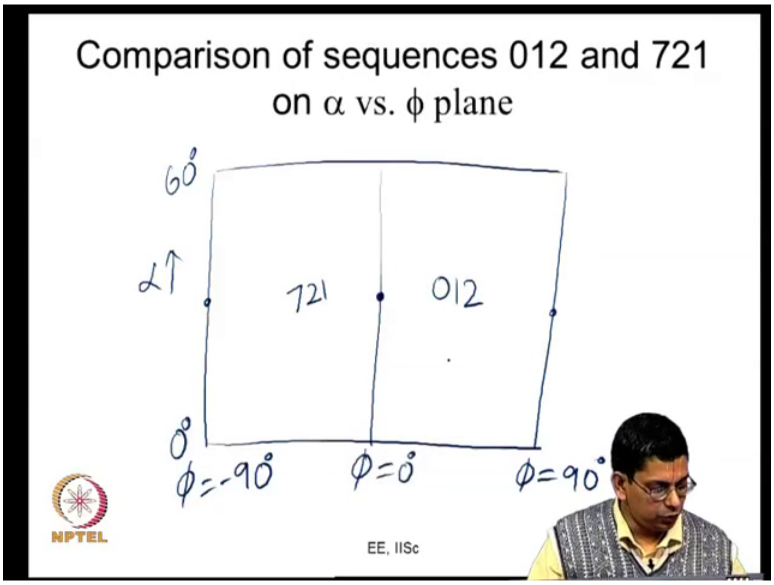

So, you can actually represent it like this what you are trying to do is let us say you can consider a particular box. Now here this is the power factor angle phi is equal to 0 degree, phi is equal to 90 degree, phi is equal to minus 90 degree so one side it is leading, the other side it is lagging.

So, you can try and see if it is generally if it is for lagging power factor you will find that 7 2 1 is better and this is for alpha, this side you can start from alpha 0 and alpha 60 degree. So, you can plot on this plane you will generally find that 7 2 1 is better and 0 1 2 is better on the leading power factor sides and actually for phi is equal to 0 and alpha is equal to 30 both are equal here.

Similarly you will find that both are equal here you will actually get a line if you solve the previous one you solve the previous one this equation I am not going to do this you can just take this is a home exercise you solve this you will get the lines that will divide this into 2 regions, one region of superior performance of 0 1 2 and the other region will be superior performance for 7 2 1 that is you will set certain combinations of alpha and phi for which 0 1 2 leads to lower loss than 7 2 1 and vice versa.

So, this combination if you do that it is already being worked out in the literature I will give you the reference also shortly. So, you can actually find out you will come up with the most optimal combination of 0 1 2 and 7 2 1 that would give you the optimal PWM method optimal discontinuous PWM method for minimizing switching loss at a particular power factor angle. So, I am leaving this exercise for you.

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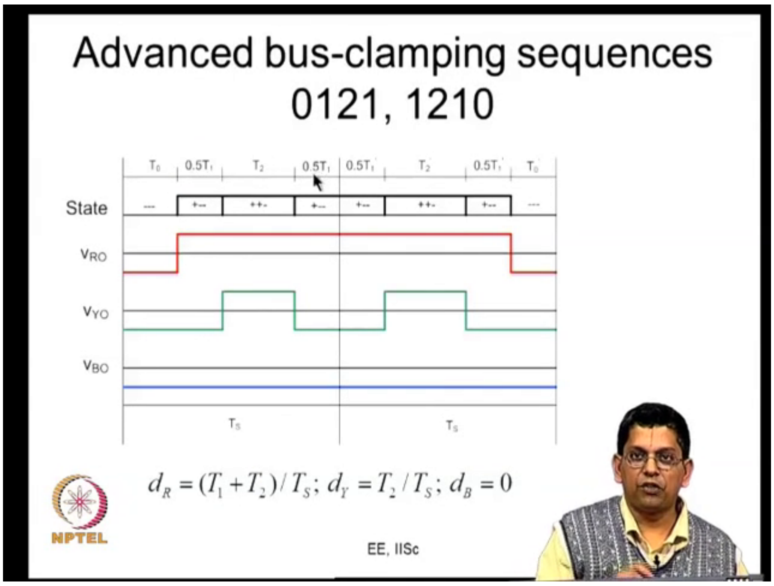

Similar exercise can be carried out for all the other sequences. iIf this is advanced bus clamping PWM you are just doing 0 1 2 1, 1 is being applied 2 times for 0.5 T 1 seconds each.

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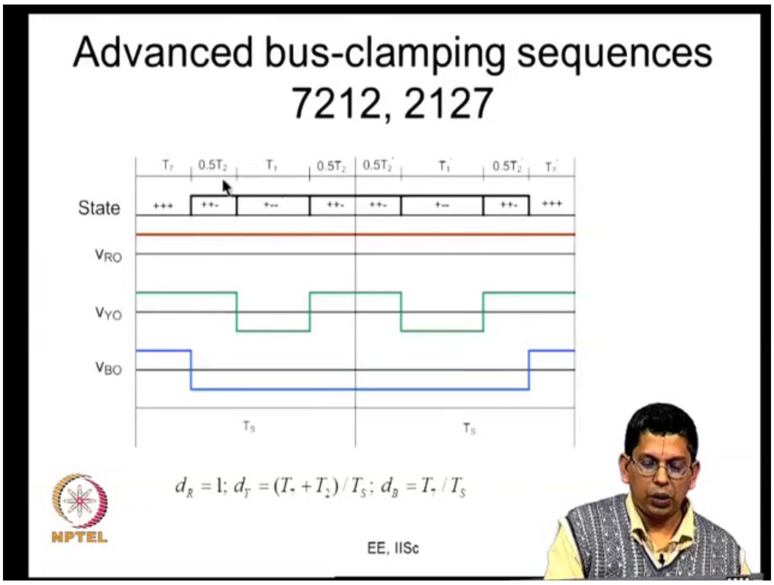

Here what are you doing 7 2 12 so 2 is being applied for 0.5 T 2 times each so these are advanced bus clamping PWM sequences R phase is clamped B switches once, but Y switch is twice as I told you this will be advantageous if the energy that you have saved by not switching R phase is greater than the energy that you are losing by switching the Y phase or in other words if the R phase current is greater Y phase current this is an advantageous otherwise this is a disadvantageous.

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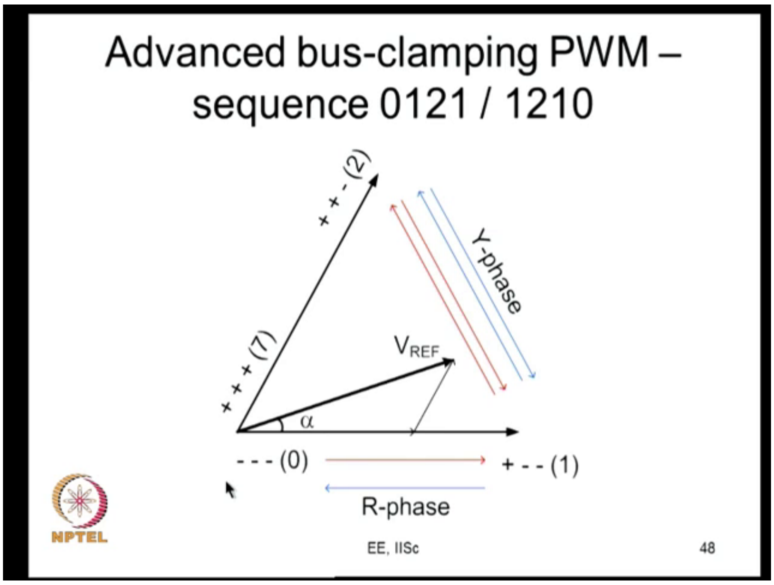

So, you should know where to use it so that is what we are trying so 0 1 2 1 I am just trying to represent it here 0121, 1210.

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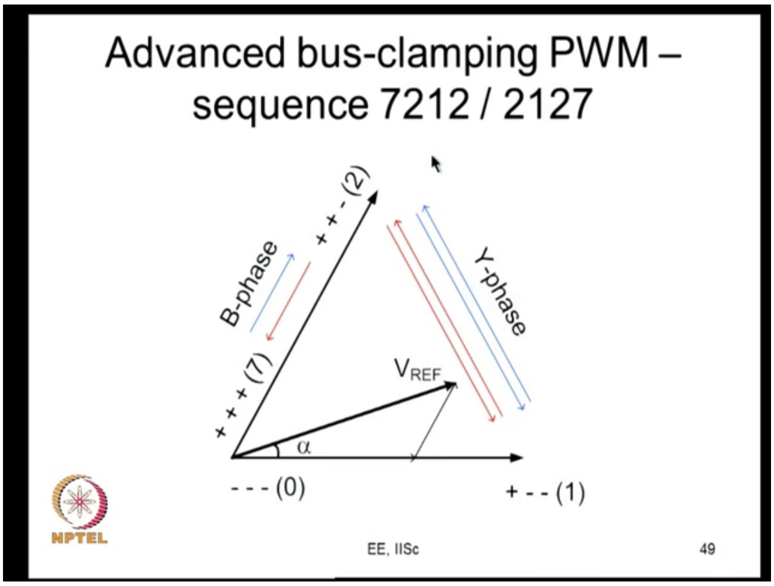

Similarly, 7 2 1 2 I am sorry 2 1 2 7 is the other sequence for advance bus clamping.

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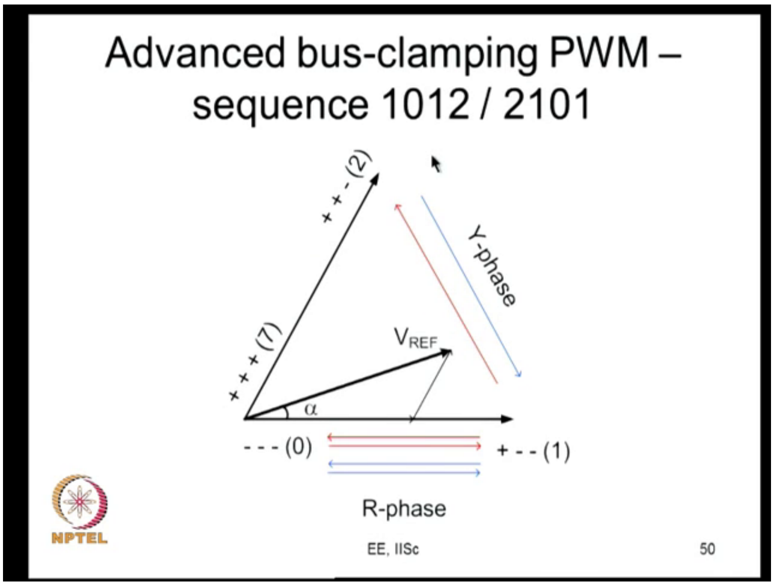

And this is 1 0 1 2 you start from 1 go to 0 come back to 1 and got to 2.

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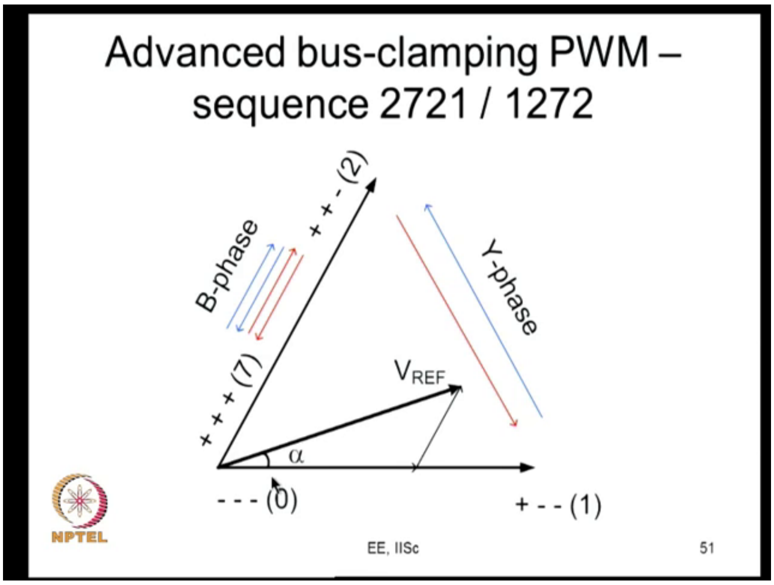

Similarly 2 1 0 1 these are all sequences is yet another bus clamping PWM sequence 2 7 2 1 or you know 1 2 72 so you start from 2 7 2 1 12 72 so these are advance bus clamping sequences so you have four of the sequences which we can call 0 1 2 1, 7 2 1 2, 1 0 1 2 and 2 7 21.

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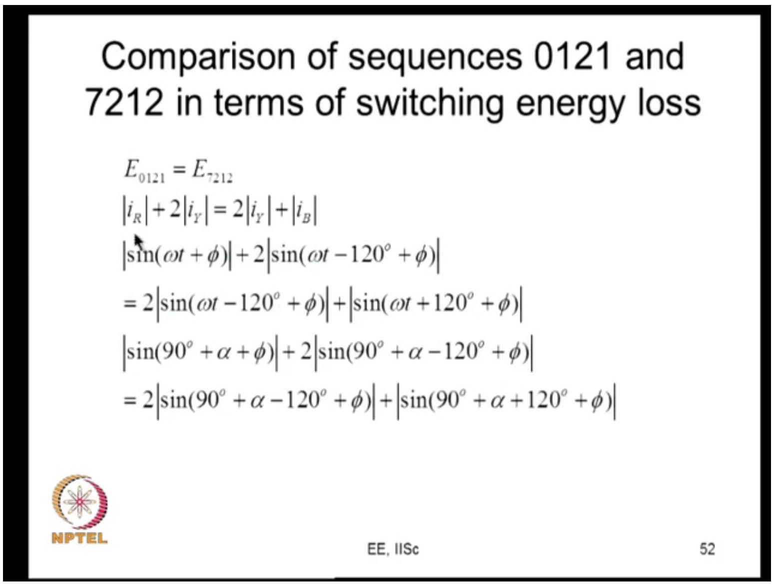

Let us take two of them 0 1 2 1 and 7 2 1 2 then we can compare them easily. What happens 0 1 2 1 R phase switches once so the energy loss is given by i R plus 2 times i Y because Y phase switches twice; i B does not switch. If you take E 7 2 1 2, Y phase switches twice so this is proportional to 2 times unsigned value of i Y plus i B here R phase does not switch.

So, you know the expressions where i R i Y and i B, so you can put in those expressions and this is we are looking at sector one therefore, omega t is equal to 90 plus alpha you actually get an equation in terms of alpha and phi you know there could be multiple solutions please be careful about that there could be multiple solutions.

And so allow for this particular relationship between alpha and phi you will have 0 1 2 1 equal to 7 2 1 2 you know their losses will be equal you can easily find the condition E 0 1 2 1 greater than E 7 2 1 2 and E 0 1 2 1 less than E 7 1 2 1 2 so that would be a way to combine 0 1 2 and 7 1 2 1 2 to come up with the PWM method which is got a lower switching loss than 0 1 2 1 individually 7 2 1 2 1 individually.

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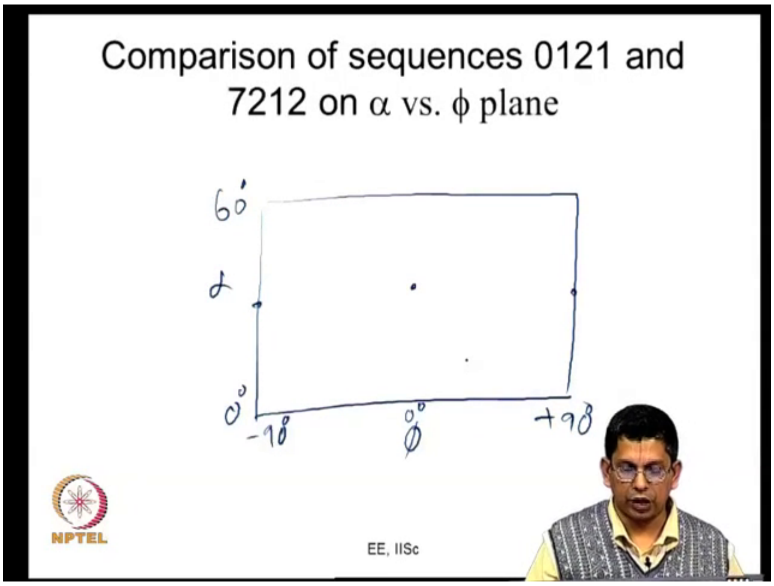

The same thing you can do you know you like what I said before you go ahead and just plot it you take a box this is phi 0 degree, minus 90, plus 90 and this is alpha, 0 degree, 60 degree you try to do this. Now you will see that both of them are equal at this point this is one point these are some points I am giving you straight away they will fall on certain lines you find out those points any way they are there in the references that I am going to give you also.

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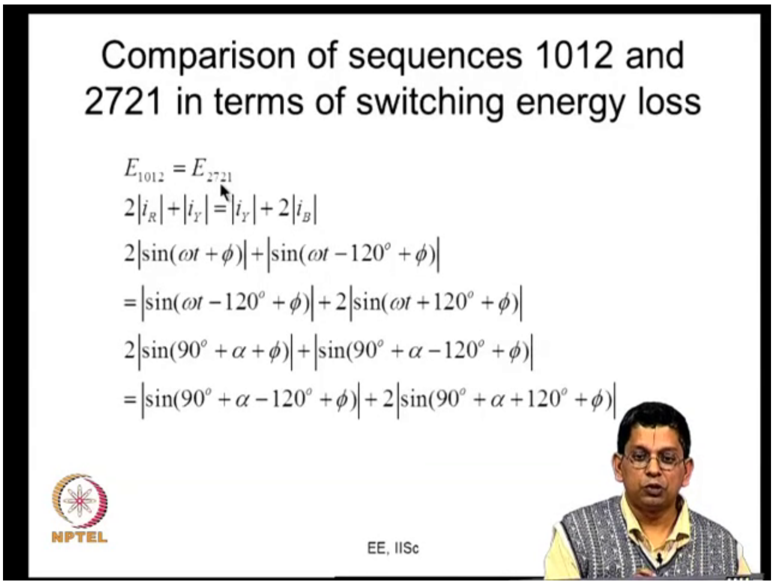

Similar exercise can also be done for E 1 0 1 2 except that now R phase switches twice, so it is 2 times i R plus i Y 2 7 2 1 B phase switches twice so it is 2 i B plus i Y B you can do a comparison this will tell you when 1 0 1 2 is better than 2 7 2 1 or vice versa and then you can use an appropriate combination of 1 0 1 2 and 2 7 2 1 which will give you lower switching loss than these two sequences put together the same way.

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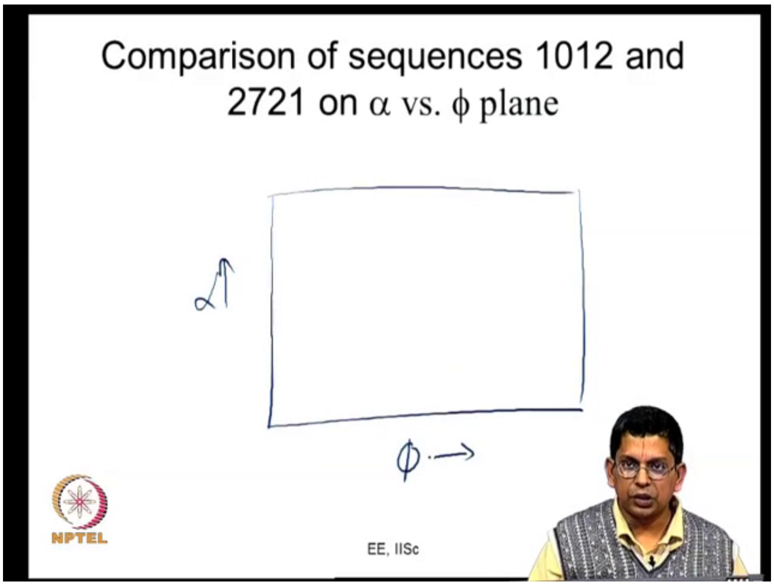

So, this exercise can actually be summarise similarly on the alpha 1 versus alpha 2 plane, you can once again summarize it on the alpha versus phi plane as we have done before.

So, it is what necessary that you have to compare only the 2 sequences with 2 of them you can compare all the sequences with each other and that is what will give you something called as minimum switching loss PWM.

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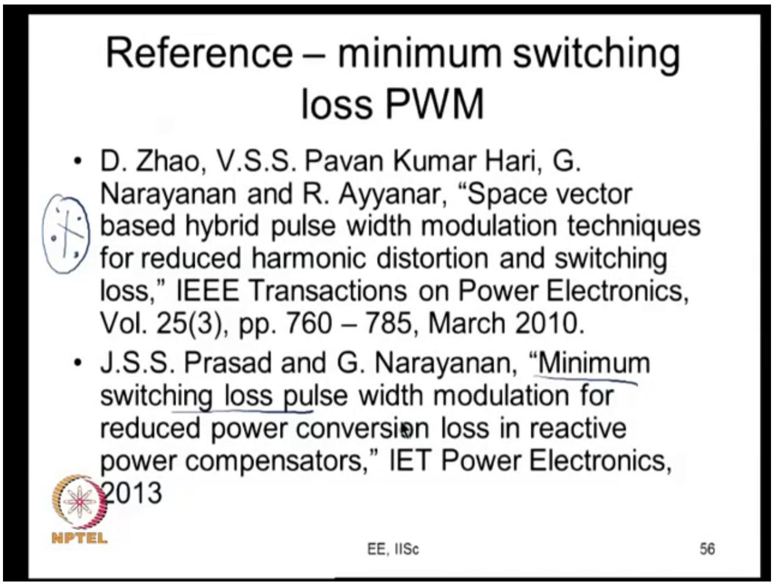

The name that you find here as minimum shooting loss PWM there is actually discussed in this particular paper. So, the alpha verses phi planes that I told you know whatever you could actually say these are all actually discuss here so you can do this as a homework and you can verify your solutions with what is actually being given in this particular paper.

So, this actually tells you how to drive a minimum switching loss PWM which is a combination of all these sequences 4 advance bus clamping sequence and conventional sequence and the 2 bus clamping sequences using these 7 sequences there is a particular PWM method which minimises the switching loss at a given average switching frequency. So, it is shown this is up an advance bus clamping PWM method.

So, it is shown that the advance bus clamping PWM sequences are better than the other sequences when you are looking at reducing switching loss at a particular average switching frequency. So, the details are available here you could actually look at it now. So, this is deals with the minimum switching loss PWM for the entire range of power factor here it is dealt with for a particular power factor this is reactive power compensator so it is actually you are looking at 90 degrees that is the stat com is going to supply power reactive power. So, if the current leading by 90 degrees so this would be a 1 particular PWM method and for this particular PWM method it is shown that the power conversion loss is lower I mean of course minimum switching loss is going to reduce the switching energy lost.

So, you know we did this simplified analysis the simplified analysis would say that there is certain amount of reduction there is a variation between the simplified analysis and the actual analysis. So, this paper shows that there is some difference between the two but never the less with the minimum switching loss PWM there is certain good amount of reduction in the switching loss.

So, for example, here the our simplified analysis prediction 22 percent reduction in switching loss, but the actual reduction in switching loss found for a actual power converter when you do the calculations in detail we are getting it to be something like 15 percent and there is a there is conduction loss also.

If you look the total power conversion loss this paper reports that there is some 7 to 8 percent reduction in the total power conversion loss that is what it reports and this is for a specific application of reactive power compensation.

So, where you have this power loss is evaluated at this thing here also you have analysis and you have the experimental results you know which are shown at some power level of few k v a, here it is shown at a power level like 100 to 150 k v a power level this is shown here. So, these are 2 papers which are directly concerned with minimum switching loss PWM, this is actually combination of advanced bus clamping PWM sequences which minimizes the switching loss at a given power factor that is what we would say as minimum switching loss PWM.

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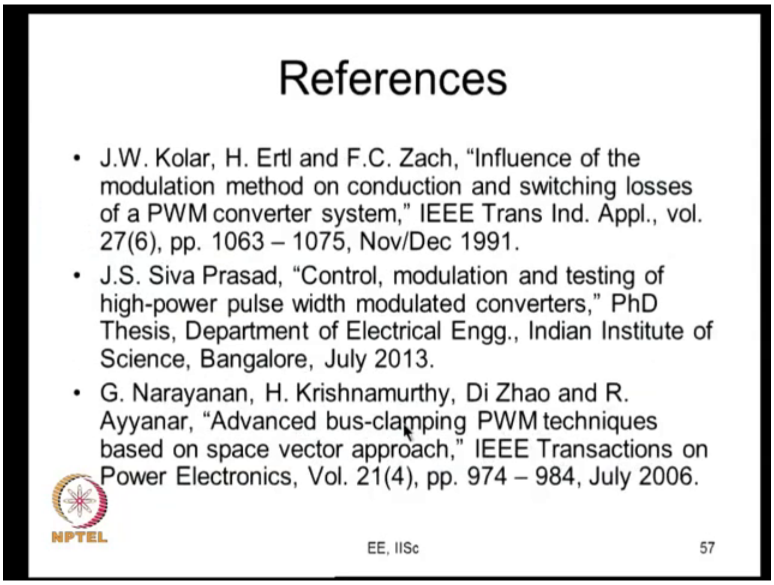

So, there are this other references this is a classical reference and there are quite a few number of other papers this actually discuss about the influence of the modulation method. These are the continuous and discontinuous modulation methods on the conduction and switching loss I mentioned this even in my last lecture.

And you know some calculation how to you know the calculation of conduction and switching loss for continuous PWM and some discontinuous PWM and advance bus clamping PWM have been done as part of this thesis. So, this is again a particular reference and here this is one which shows the advance bus clamping PWM some specific advance bus clamping PWM which uses 0 1 2 1 and 7 2 1 2 they actually give you a lower switching loss at high power factors s, this talks of some specific PWM methods. So, these are actually useful references.

So, I mean I hope that you know; thank you for your attention up to this point. And I hope that this lecture was useful to you and you could actually look through these references which will give you good information on how to design PWM methods that would reduce switching loss and total power conversion loss. So, PWM methods are very useful in reducing the switching loss and thereby increasing your efficiency of power conversion.

So, I thank you very much for your interest in that I hope that these lectures in this module both are useful to you. And I hope that the lectures where all useful up to this point of time. And I hope that you will have sustained interest in following the next 3 modules which are yet to come.

Thank you very much for your interest. Bye.