Pulsewidth Modulation for Power Electronic Converters
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Lecture - 32
Evaluation of switching loss in three-phase inverter

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

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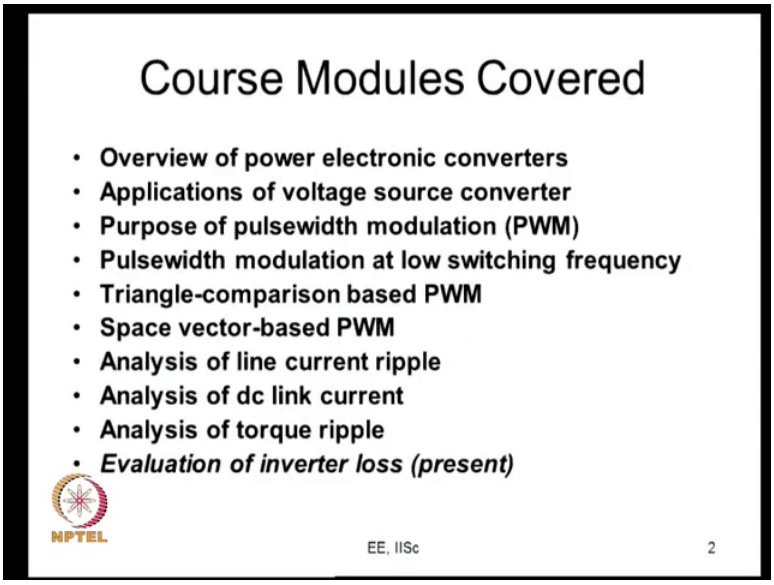

So, we have this course going on, we have covered quite a few modules in this course, each module like we probably the very first module on power electronic converter is little on the longer side many of the other modules are probably two to three lecturers and maybe three or four lectures and so on so forth.

So, we have looked at an over view of the various topologies and some applications of over view of the applications of voltage source converters, some basics of pulsewidth modulation. Then we looked at this generation of pulsewidth modulation with low switching frequency. This you know the one purpose is to learn about that, so we keep the number of switching angles low. So, that we start understanding how the harmonics are and how they affect the performance etcetera. The other reason that why we go for low switching frequency is when the power levels are pretty high, therefore the inverter cannot really switch at high frequencies because every time it turns on and turns off the every times; I mean every time it device turns on and turns off there is certain amount of switching loss energy lost. And therefore, it cannot turn-on and turn-off more than a few cycles in a second.

So, that is why it is a mini high power inverters would switch at rather low switching frequencies. So, you might just have a few hundred hertz of switching frequencies for example. I said medium power levels you can look at a few kilowatts kilo hertz of switching frequency and at low power convertors like MOSFET convertors you may even think a 100 kilo hertz etcetera going there now.

Incidentally, today our I mean this present module our discussion is being actually on this evaluation of inverter loss and is actually switching loss. And that switching energy loss is basically the reason for the high power inverters operating at low frequencies. Then after that low frequency PWM generation we also looked at high frequency PWM generation, both through the triangle comparison approach and also through the space vector approach. And after that we have been focusing on certain analytical portions like, how do we analyse the ripple that is there in the line current when the; I mean if here of course we are assuming that the switching frequency is much higher than the fundamental.

Similarly, how do we analyse the DC link current, how much is the rms current flowing through that what is its DC components so and so forth. And again analysis of the ripple torque; how much ripple torque. So, these are the previous modules we covered now.

So, presently we have been dealing with this evaluation of inverter loss. In the last lecture we covered the conduction loss aspect and today we will be doing the switching loss.

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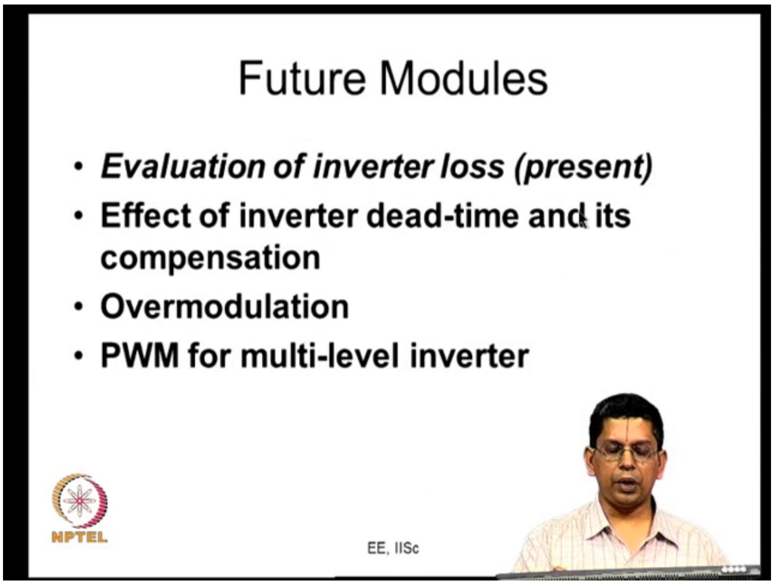

So, that is what we will continue today. And the future module which remains to be done are actually the effect of the inverter dead time and its compensation. So, the nonidealities there is a power drop that causes conduction loss which we dealt with in the last class. And again the other nonideality in the actual switches is that they take finite amount of time to turn-on and turn-off and there is certain amount of switching energy lost, and that is the switching loss which we are dealing with in this present lecture.

In the future modules what we will do is; since it takes some finite amount of time one consequences of that is the loss the other consequence or other thing requirement is that you know the complimentary devices it cannot be switched to really in a complementary fashion; that is the movement you switch on one switch off one device you cannot switch on the other, you will have to wait for a while before you can switch on the second device. So, that is what is called as dead time. And that has certain impact on the output voltage of the inverter. And we would be looking at that and how to compensate that in the next couple of lectures mean the next module.

And again we would look at over modulation that is where we can operate in not really in the linear modulation zone, but we go into a non-linear modulation zone all the way till square wave mode or six step mode. And then the final module will be PWM for multilevel inverter.

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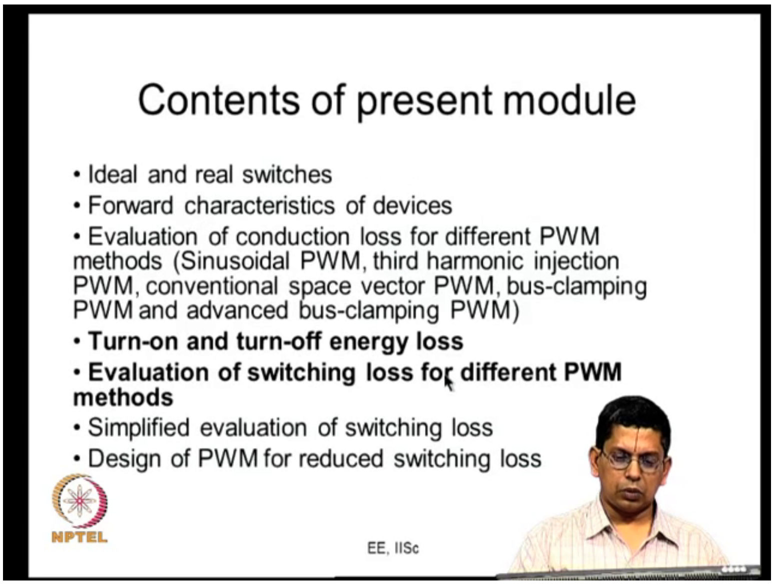

So now, we are back to the present module. So, we looked at ideal and real switches and we looked at the forward characteristics of certain devices. For example, you know MOSFET behaves more like resistance when it is on, whereas bipolar transistor has VCE sat I mean its device voltage tends to be reasonably fixed, I mean changes only moderately with current. So, it is more I mean modelled better as a voltage source in its on-state or maybe a voltage source in combination with a resistance.

So, such kind of forward characteristics and how you would go about evaluating the conduction loss at any given modulation index of the particular PWM method and again how would you do with for various PWM methods. These for the subjects we looked at last time.

Today our focus will be on the turn-on and the turn-off energy loss, because these real switches take a finite amount of time to turn-on and turn-off. And before let us say the voltage falls down to 0, the current builds up. And therefore, there is a considerable amount of power dissipation during the turn-on transition; this story similar during turn-off transition. So, we would look at that energy lost in turn-on and turn-off, we will try to get some idea on the energy lost. And we will try to see how we could possibly evaluate the switching loss for different PWM methods. And subsequently we would go on towards simplified evaluation and switching loss and design of PWM for reduced switching loss.

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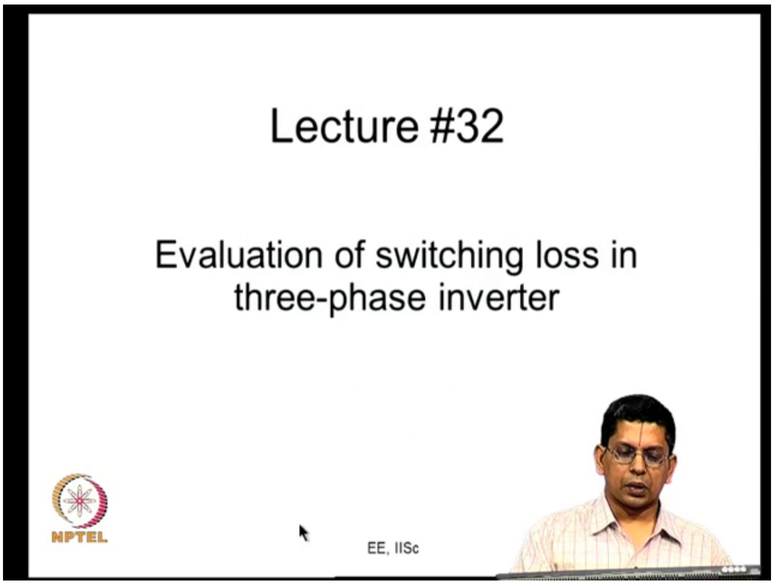

So, as I just mentioned before we would look at evaluation of switching loss in three-phase inverter.

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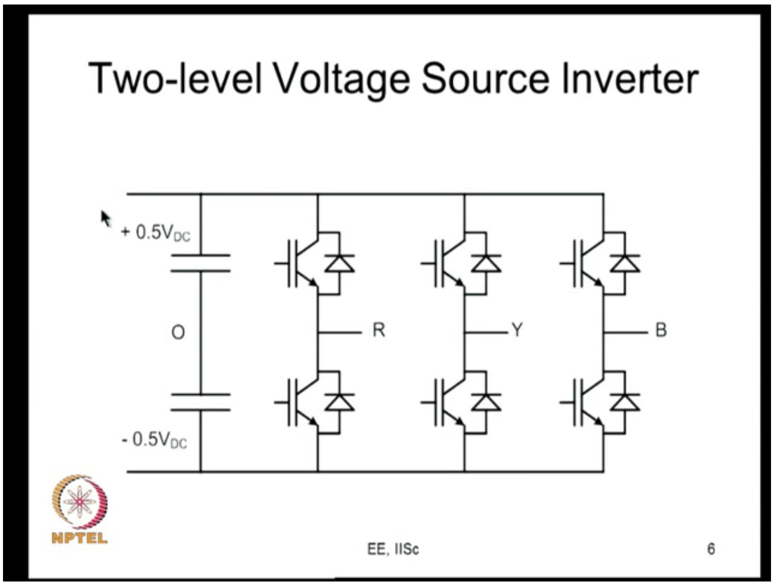

So, this is the three-phase inverter. So, every leg is a, it is a pair of complementary switches. So one turns on, I mean turns off the other turns on and vice versa. But during every time there is a turn-on and turn-off what happens see; initially there is this voltage you know when well let us say this is conducting so the entire voltage is being blocked by this. So, when this device is to be turned on then what happens there is voltage across that and the voltage has to collapse down to 0, and the current has to rise through this particular device. So, before the current you know I mean; I mean the current starts rising well before the voltage starts falling. And therefore, there is a certain amount of loss here, which is what we are going to look at today.

So the loads are connected and they will be fundamental and the harmonic components also. As we will see with the harmonic components their effect on the switching loss would be negligible because the harmonic currents themselves might be negligible compared to the fundamental current when you are switching at fairly high frequencies. And of course, switching losses mainly a concerned at high switching frequencies. And this is in the load and this is the DC side and here DC sources really connected there. And how much DC link current flows etcetera or the capacitor current flows we will be had seen previously in a earlier module.

So, today our focus will be on what are the kind of losses that you will have in these IGBT and diodes. As I already mentioned to you, let us say for one direction of current conduction will be either this IGBT will conduct or this diode will conduct. For the other direction of current either this IGBT or the diode will conduct. So, current will actually commute from here to here or here to here depending on the direction of the current now.

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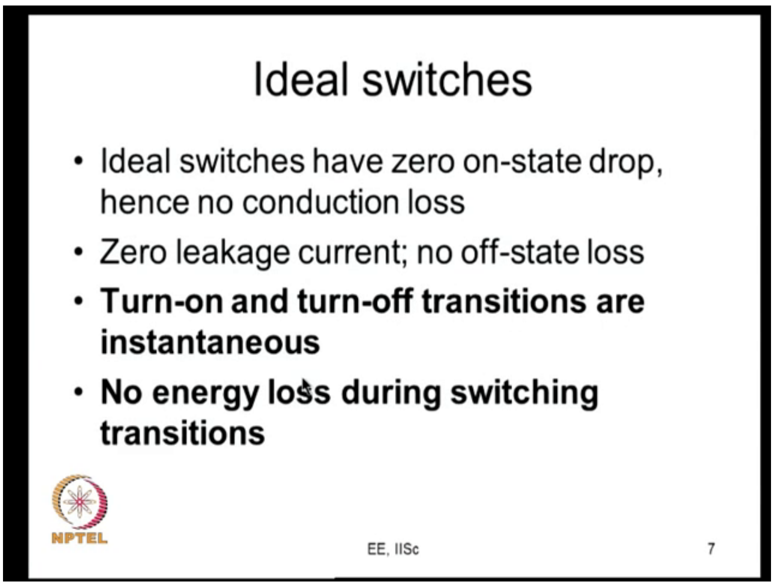

So, as we saw earlier ideal switches have zero on-state drop. And how much ever current may be flowing through that? The voltage across that is zero and therefore the product of voltage and current is zero. And therefore, there is no power dissipation. Therefore there is no conduction loss in an ideal switch. Also let us say an ideal switch is in the off-state, then there is supposed to be some leakage current if the switch is ideal leakage current is zero. So, once again the product of voltage and current is zero because current is zero, so there is no off-state loss.

Again the turn-on the turn-off transitions are instantaneous; the moment it starts turning on it is already on, the moment it is started turning off it is already off; so there instantaneous turn and turn-off. During turn-on the voltage is expected to fall down from whatever it voltage it is being blocking down to zero, when the current is expected to rise from zero to whatever the current it is expected to conduct. These two will happen instantaneously. Similarly, during turn-off whatever current it is being conducting will fall down to zero in instantaneously. And similarly the voltage across that will rise instantaneously. So, this is what happens in ideal switch now.

So since, there is no finite duration there is the voltage falls and the current rises or you know the current falls and the voltage rises, both are never high concurrently and therefore there is no energy loss during switching transitions in an ideal switch.

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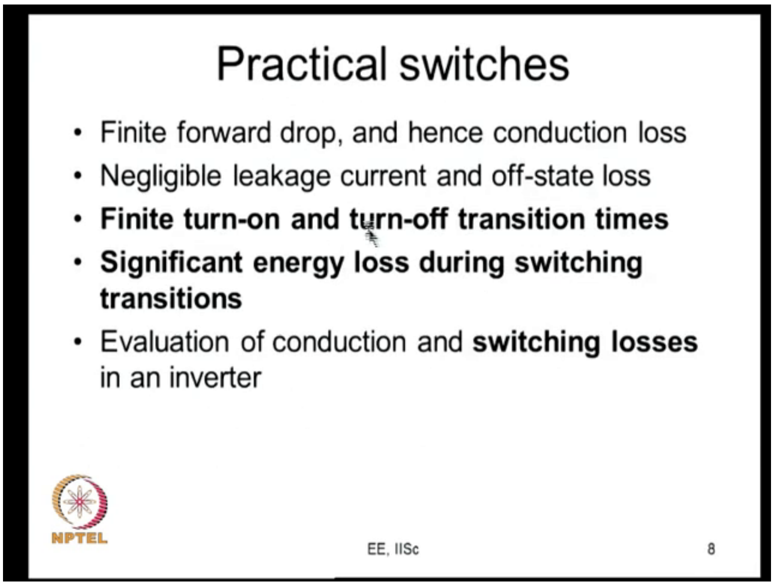

But that is not the case in a practical switch. That is we have seen before: there is a finite amount of power drop. Means whatever current might be flowing through that this power drop multiplied by the current is a power dissipated in the transistor. And therefore, there is some conduction loss which was our subject for discussion in the last class lecture. Then, you know even in a practical switch the leakage current is negligible whatever loss it could cause is negligible thankfully and that there you know you normally ignore the off-state losses in most power semiconductor devices.

So, how about the transitions? The turn-on transition is finite then that is probably cause for the problem now. So, turn-on meaning the voltage has to fall down to 0, it will take a finite amount of time for the voltage to fall down to 0. Again the current has to rise from 0 to the full value. Will it rise instantaneously? No, it will also take finite amount of time. And in fact, the current would rise first and then the voltage would fall as we will see shortly. And therefore, what happens the product of current and voltage is very high, not just significant the product is very high; the voltage can be as high as the DC bus voltage and the current can be as high as the current that it is conducting.

So, the peak power can actually be the product of the DC bus voltage and the instantaneous load current. And that can actually be very high it can be in kilo watts it can be in tens of kilo watts. For example, if you are switching 600 volts at 100 amperes current. So let us say there is a particular instant of time when the device is blocking still blocking entire 600 volts, but the current through that is resent to 100 amperes. And therefore, the product of thing is 600 volts into 100 amperes. So, you can see that it transcend to tens of kilo watts.

So, there is a significant energy loss during the switching transition. So, one of our things today will be to actually get some idea on how to calculate this, you know how to get this losses etcetera. And we will have to go about evaluating the switching loss, like we did for the conduction loss is the last lecture today our focus will be on evaluating the switching loss.

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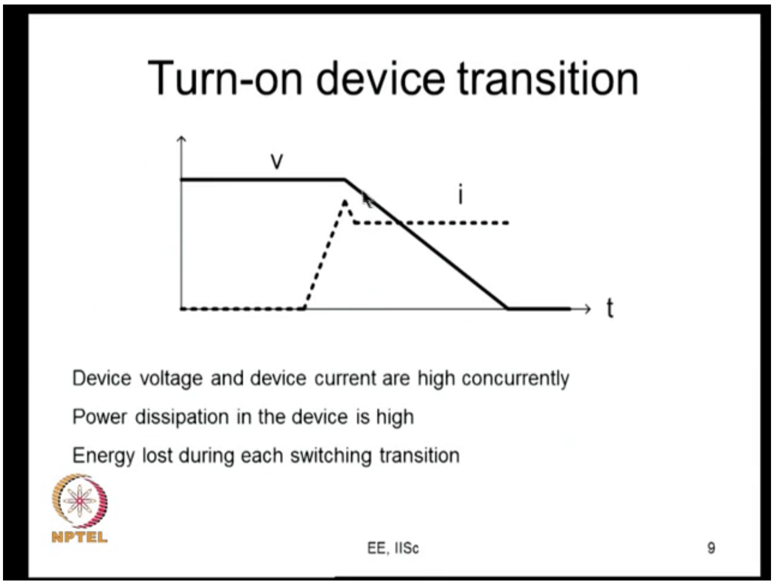

So, this is something that tries to illustrate that turn-on process of an IGBT. So, it is blocking certain amount of voltage, this voltage let us say is the DC bus voltage; this devices is been blocking this voltage. So, this device is being turned on, therefore the voltage is then starts actually falling. And I have shown this is linear, many a times the voltage may fall rapidly and then the voltage based load on and fall like this also. So, the let us say that this is falls like this now.

So, you can see that you know the moment the voltage falls there is certain voltage difference between the DC voltage in here which is actually being blocked by the diode. So, the diode is already a reverse bias and it is blocking some amount of voltage. Therefore, you can see that the diode has stopped conducting by the time the entire amount of current that the diode was carrying prior to the turn-on transition is already been transferred to the IGBT. The IGBT current actually is reason, almost its full value by the time the voltage starts falling.

So, now on top of it what you really have is it is a little on the higher side. So, this is basically the reverse recovery currents, it is just the load current plus the reverse recovery current of the diode flows through that and after that its steady current here. So, the well before the voltage starts falling the current has reached its peak value; I mean by the time and well before that the current started rising. And the time that the current takes to rise is typically call the rise time. And the gating signal might have been given not just at this instant, but little ahead of this instant. And there is certain amount of delay time which is usually called as a turn-on delay time.

So, which is not much of concern now for as, because our problem is essentially we are looking at the voltages of the current; so this is how let us say this is you know illustration of a typical turn-on transition. So, the voltage is falling here, but before that the current as a reason. Now, if you consider the product of voltage and current you can see that the product of voltage and current is zero up to this point, but from this particular instant the product of voltage current increases. So, it will go to high value. And then excuse me, it will start falling; it will start falling reach here now.

So, starting from this instant to this instant there is going to be a significant amount of power loss and that is; what is the power loss due to this transition. And the peak power dissipation is going to be somewhere here, which is roughly equal to the DC voltage multiplied by the load current. So, this is what I said, if this is 600 this is 100 amperes it is the product of that.

Now, let us say which is going to happen. So, there is certain amount of energy. So, if you multiply v and i and you take you integrate that over this interval which is the switching interval; that is going to give you the amount of energy that is being lost because of this on turn-on transition. So, that is the amount of energy loss which is called as the turn-on energy loss.

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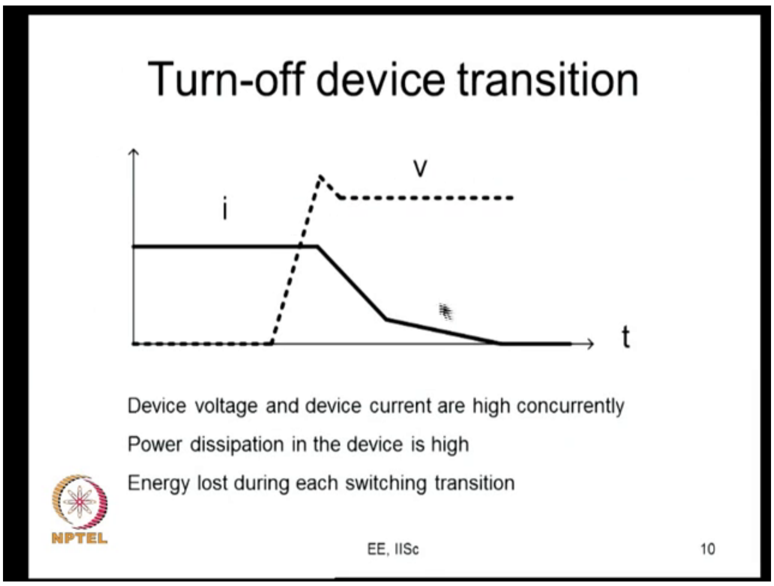

Similarly let us say the device is turning off; it is conducting some current and that current falls when it is turning off. So, it may fall rapidly in sometimes it may fall rapidly initially and then it is slow downed. So, it is kind of more gentle than this which you can you know, but sometimes you can represent that has a double slow. So, that is what I am saying is the current instead of falling sharply down, it initially falls sharply down and then slowly you know tapers down it.

So, this part it is represented like this; I mean asymptotically like two straight lines for purpose of convenience. And this is sometimes called tail current- t a i l tail because it is like a tail, so this is that. So, before the current starts falling once again you see that the voltage has hit its limit. And there is certain amount of small amount of voltage pike also, see here I am just trying to illustrate this these are not exactly the switching characteristics as you would really see when you conduct an experiment measure switching characteristics. I mean you see that there could be a little different, but I am just trying to show how it will be. For example, this may not be a straight line, but this could be something different, it depends on the parasitics and many things like that.

But, what you can normally sees you can see certain amount of over voltage pike which is caused on account of this di by dt etcetera when a time it turns on and turns off there is on over voltage spike. And so, that is the reason if let us say this is the DC bus voltage you would choose your device voltage rating to be significantly higher than your DC bus rating. So, for example, if you have a twelve ended old device you will not use it for a DC bus voltage like 100 volt; I mean of 1000 volts or 1100 volts, you may use it only up to something like 800 volts some 600 to 800 volts is a DC bus. So, for 600 to 800 volts of DC bus you will be using a 1200 volt to one.

This also assumes that you have done a very good bus bar design, you have to make sure that the strain that (Refer Time: 15:39) are all very low otherwise this spikes can even be much higher. That is you know it is when it is all turning at these instants if there is lot of di by dt etcetera, so there are the parasitic inductances can actually cause very high amount of voltage is there.

Anyway, our present problem is not really look at those parasitics and so over voltage pike and so on and so forth, but our present problem is to understand the turn-off transition and what is the device lost during the time. So if you say- if this is how the current falls and if this is how the voltage across the devices is then it is a product of these two. As you can see here is the product is almost 0 and again here also the product is almost 0; that is this is before the turn-on. So, during this time should have been conduction loss those drop of this would have been the power drop that is actually very small. Again here there is a conduction is 0, so this is off-state there is no loss now. But over this interval from here to here you find that there is good amount of power dissipation.

So, if you plot the product of v and i you will see that it sharply rises and reaches a peak somewhere here and then starts falling gradually, and starts falling and from here the fall might become more gradual and finally it will come and reaches 0 here. So, this is the instantaneous power dissipation, this is how it varies a product v and i. And if you calculate the area under that you integrate this over this switching interval you are going to get the energy lost during turn-off transition.

So, this is what is called is E off energy loss (Refer Time: 17:06) turn-off transition.

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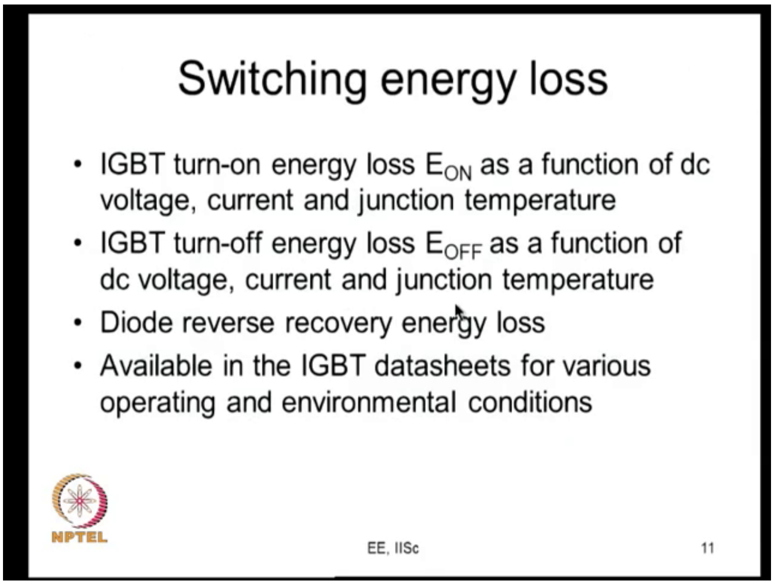

So, this E on and E off turn-on energy loss and turn-off energy loss are important for us to evaluate the overall switching loss. So, the IGBT turn-on energy loss how much is at 10 millijoules, 50 millijoules, 75 millijoules, 120 millijoules, it actually depends on the DC voltage. Obviously, because you can see that the power is a product of voltage and current. So it depends on the DC voltage, it depends on the current and it also depends on the junction temperature. It depends on the device transition times; here I am talking of a particular IGBT.

So, for a given IGBT if we switch it at higher voltage you would expect that the E on to be higher. Similarly if you switch it at higher current you would expect the E on to be higher. And again junction temperature also has an influence on that. So, the operating temperature may be junction temperature and our case or something whatever is related. And junction temperature is usually about 120 degree Celsius is taken as, the highest permissible junction temperature.

So, about the turn-off energy loss which is designated by this I mean which is we use that symbol E off, this is also functional DC voltage. Of course, you know if you are switching off a device it has to have certain amount of energy lost. If you a switching only 100 or 200 volts the energy loss going to be lower, if you are switching 500 and 600 volts the energy loss is going to be much higher. Therefore, you can see that it depends on the DC voltage or increase is in DC voltage that is that was being blocked.

And it also depends on the current that the device is going to conduct or it was conducting, because the turn-off loss it was conducting some current. So, it depends on how much current it is; if it is 20 amperes I mean the loss has to be much higher than if the current is 10 amperes. We could even say they are roughly proportional as far as current is concerned.

And also it depends on the junction temperature. So, there is also diode reverse recovery energy loss, you not only have the IGBTs you also have the anti parallel diode. And every time you know the diode is turning off there is something called what is called as reverse recovery process in that. So, there is certain amount of energy loss associated with that so this loss is also known. I mean these all we need to get them from the IGBT data sheets.

So, there is an operating IGBT data sheet let say there is a 75 ampere 1200 volt IGBT with the anti parallel diodes. So, that would give you this E on E off, it might give E on at some 2 or 3 different DC voltages, it will give a over a range of current something like 5 percent or 10 percent to the rated current. It will give E on and it will give again for 2 or 3 temperatures either junction temperature or case temperatures.

So, same way the E off data (Refer Time: 19:47) also be available from the IGBT data sheet and the diode reverse recovery this may also be available from the data sheet now.

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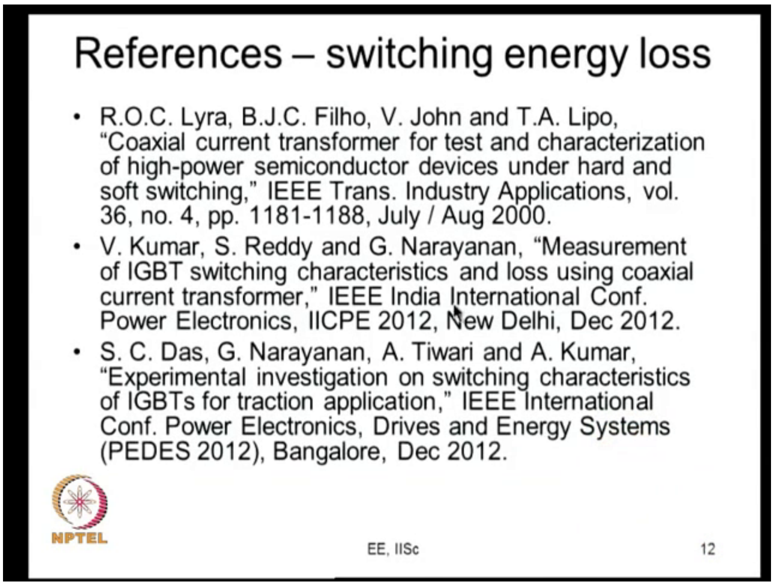

So, these are certain references which tell you how these measurements can be made. For example, it is a little difficult to measure these current. Now let us say you got to measure this current. It is all the current rises. It is very difficult to put in a current probe anywhere here. For example, you can put a current probe here; this is all within a package and they are all tightly connected. Meaning; the parasitic inductor is an very low, so you really cannot put a current probe anywhere here or so. So you need some special arrangements to do that. And once such special arrangement is actually what is called as a coaxial current transformer.

So, what is done is that you have a module there is a particular device and there is a particular terminal of the device, and this coaxial current transformer it has got a primary winding which is got a coaxial structure. And so you know like current will enter let us say through the inner length of the coaxial primary and will go out to the outer limb into the bus bar plate or whatever.

So, the primary will have a coaxial structure and the secondary you know there is a annular region between I mean the middle of the primary. So, secondary will be seated inside that. And therefore, that will have a very low amount of leakage inductance. So, this coaxial current transformer has a particular kind of structure and has low leakage inductance. And therefore, you know it is possible for you to use this and make measurements.

What will happen is the inductance is high? If the inductance is high then as I just mentioned a while back and I have mentioned in some previous lectures the devices will fail, because the parasitic inductance increases there is high di by d t. So, l di by dt is going to be causing some more voltage spikes and the devices are going to have over voltage failure. So, you cannot introduce current measurement system which will actually increase the inductance, you have to do it in such a fashion that the inductance is not increase significantly. And coaxial current transformer is one way of you know doing that. So, this will not give you much you know great amount of increase in the current you can still go about doing it now.

So, these are some papers which actually talk about these coaxial current transformers this is one paper and how you can go about measuring the switching characteristics. I had given you some switching characteristics more indicatively, its possible for you to measure these characteristic curves. You know this is how the data sheet values are actually being given or whatever. And sometimes a data sheet may not give you the correct value exact value that you want, you might want data for 800 volts DC bus, but what may be available is only for 600 volts and 1000 volts.

So, you know that there are time zone you might want to measure and so are the data may be available for some case temperature you may be operating at some other case temperature. So, many a times even though you have data sheets we might want to make these measurements and as newer and newer devices is come you actually have to do this kind of characterizations. So, this is actually a paper which talks of how do you do this characterization, how would you measure the switching characteristics of semiconductor devices and using a coaxial current transfer.

So, this is the second one is much later measurement of IGBT switching characteristics and loss using coaxial current transformer. So, this reports certain things on how exactly you can build one and design, I mean design and fabricate one and how you make certain amount of measurements. So, these are all about you know measuring this E on and E off.

Now third one is also something similar, whereas in an first two cases the use coaxial current transformer here this Rogowski Coil is used and these are actually high power traction converters. So, in the traction converters how would you measure the switching characteristics of IGBTs. So, that is what it is bought.

So, these are some references which can help you understand this E on and E off, like how you can measure this turn-on energy loss and turn-off energy loss, and how this turn-on energy loss and turn-off energy loss vary with the operating conditions and the environmental conditions. By operating conditions I mean like things like the DC bus voltage and the current that is being switched, and the environmental condition I mean the let us say the ambient temperature.

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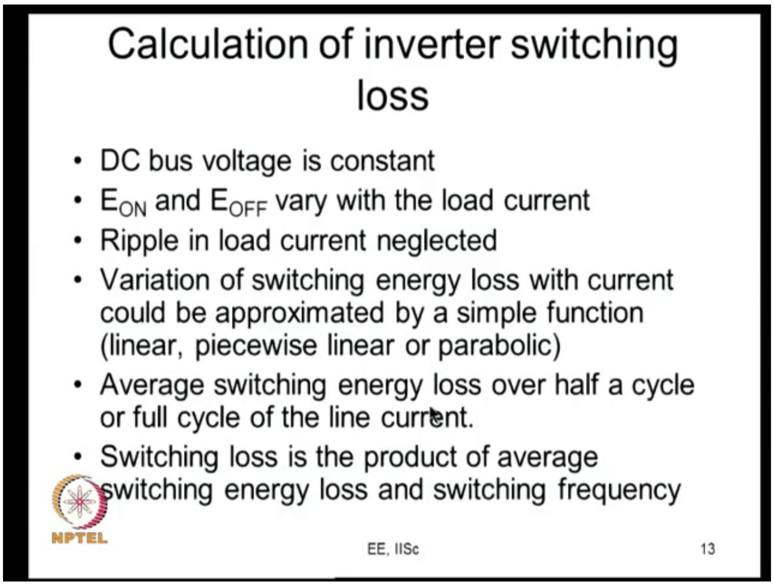

So, those are some references which could give you better inside into that. Now, let us say this E on and E off are available.

Now how would you go about calculating the inverter switching loss? So, one assumption we normally do is DC bus voltage is constant; that is you have an inverter and the inverter is being switched it has some DC voltage and you know is being switched and it is applying some AC voltage on a load or let us say a motor something like an induction motor. So, actually the DC bus voltage will be varying over line cycle there will be some ripple on that, there could be some 300 hertz ripple 140-50 hertz ripple whatever. But what we are you know one simplifying assumption we make which is reasonable a is that the DC bus voltage is constant, whatever variation is there in the DC bus voltage we are ignoring that.

Then you have this E on and E off which are available in the data sheets in sometimes there could have been measured as I was just talking to a while back. So, these E on and E off vary with the load current, you can say roughly proportional to the load current. So, they vary with the load current now. So now, what is this load current? The load current has the fundamental component and also is got harmonic components. Now at fairly high switching frequencies you would say that the harmonics are fairly negligible compared to the fundamental current; so this is an assumption which we have made earlier also while calculating conduction loss, while calculating DC link ripple current; I mean DC link current we did these.

So, the same kind way we can say that the harmonics are the ripple in the load current can be neglected. So, you can consider only the fundamental component of the load current now. So, what you need to now do is you have to look at the variation of the switching energy loss; that is variation of E on and variation of E off so with current. So, if current varies in a sinusoidal fashion E on and E off would also vary probably in a roughly in a sinusoidal fashion.

So, now this variation you can E on can be expressed as E on as a function of i, similarly E off as a function of i. So, this data will be available for you from the data sheet. So, you might be able to approximate that relationship by a simple function; say sometimes a linear function, sometimes a piecewise linear function or let us say parabolic function, so some such approximations might be possible for you.

So, once you know this you know the relationship between the energy loss and the current and you are also simplified it in some sense that the calculations can be easier. Once you have got then you have to calculate this average switching energy loss over a half cycle or full cycle of the line current. So, here it is easier for example, if it is a nice function for you. For example, if the average switching loss where is like a rectified sinusoid it is much easier for you to do the calculation. So, that is why you make use of some simplifying functions here.

So, now the switching energy loss since we have expressed it as a function of current and the current is again a function of time or fundamental angle you can integrate this switching energy loss over one half cycle of the current and you can consider its average value. That average value will give you the average switching energy loss.

So, what do you mean by that? See there is an inverter leg; now that inverter leg let us say it is switching a current the load current is about 100 ampere peak. If the inverter leg is switching a 100 ampere current then the switching energy loss suppose to be high. Same time, if it is switching only 50 amperes the switching energy loss is expected to be lower may be roughly half. If it is switching only something like 1 ampere or 2 amperes switching energy losses much lower than that.

Therefore, the switching energy loss varies with current, a current varies in a sinusoidal fashion the switching energy loss might also vary in a sinusoidal fashion it is arguable whether it would vary in a sinusoidal fashion or not is a question well sometimes you can approximate and say that it could be in sinusoidal fashion. But it certainly varies with the current and therefore with the fundamental angle. So, there is something called average switching energy loss that you would actually calculate.

So, this average switching energy loss means like for one turn-on and turn-off this is the amount of average loss I mean the energy that is lost if you multiply that by the switching frequency of the inverter you would be able to get calculate the switching loss. So, this is roughly the procedure for calculation of inverter switching loss; it is fairly simple. So, you basically need this E on and E off and you have this simplifying assumptions, and E on and E off as functions of current and you ignore the harmonics etcetera you can go about doing it now. So, there some little catch now whether it is a continuous PWM or it is a continuous PWM as that is what something we will come down to now. But this is roughly the procedure.

So, what will happen if it is discontinuous PWM? There will be bus clamping and during bus clamping the energy loss will be 0, the energy will not there will be no switching energy loss because there is no switching whenever particular like this clamped. Let us come to that little later.

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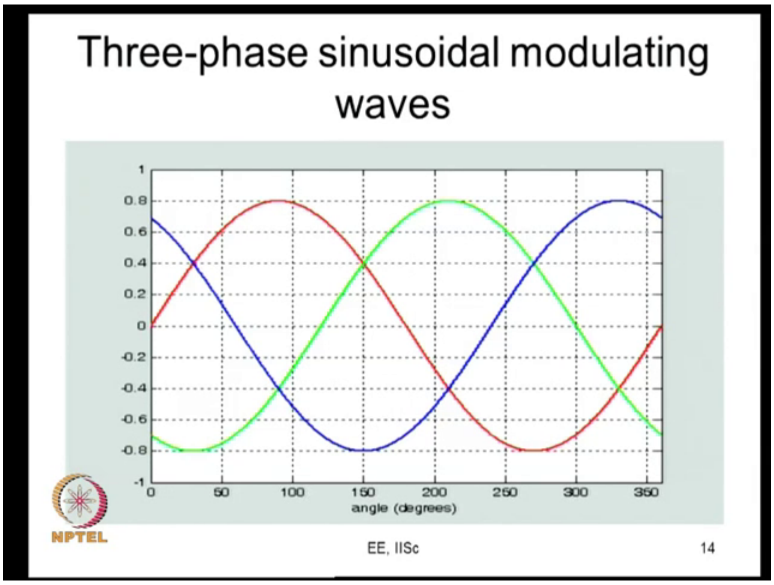

So, let us first look at sinusoidal PWM. So, three sinusoidal signals r y and b: y phases being represented by a green signal instead just for it is easier to see here. Therefore, I am given it as three say modulating signals. And you would have of course, comparative the high frequency triangle of carrier and produce the PWM signals. So, comparison of r phase with the carrier and y phase with the carrier and b phase with the carrier would give PWM signals which would fetch the r y and b phase legs as we know very well.

And soi the inverter is running. So, there is some current flowing through that.

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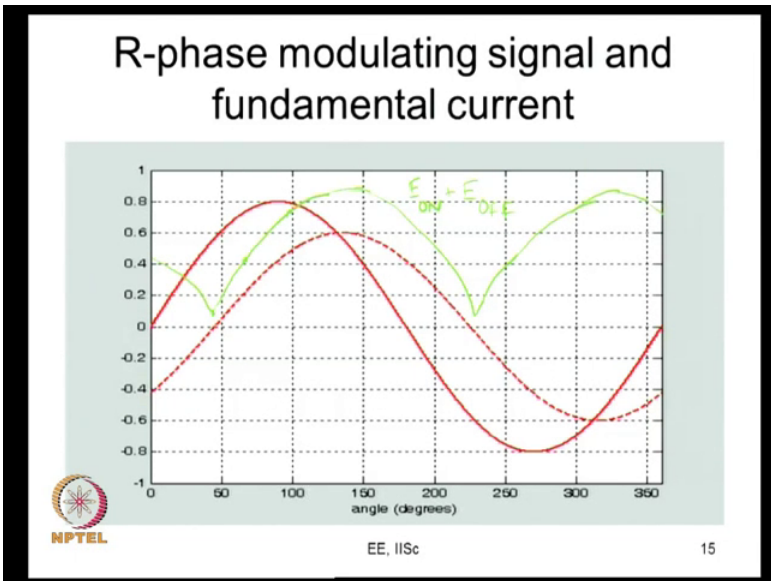

Now, let us say this is the amount of fundamental current flowing through that. So, this is the r phase modulating signal. So, the r phase fundamental voltage is proportional to this, here I have shown it as something like modulation in x of 0.8. So, this something like you know 0.8 into v DC by 2 would be the peak phase fundamental voltage; let us say v DC is 600 volts. So, v DC by 2 is 300 volts; 0.8 into 300 is 240 volts. So, the inverter is applying a peak phase fundamental voltage, a fundamental voltage whose peak value will be 240 volts in this case.

Let us say that is being fed to a three-phase load and it is a linear load. So, it drags some sinusoidal current. So, the non sinusoidal part that be this is the only the fundamental component of the voltage, there is also the you know this represents the fundamental component of the voltage there are also harmonics, those harmonic voltages would cause harmonic currents, but we assume that the load filters it out very effectively they are at high frequency harmonic voltages are high frequencies and it is effectively. So, therefore, it is effectively its only the fundamental current that is being considered here. So, let us say this fundamental current will as I said actually there could be a small ripple, but you can ignore now.

So, when you have this current, so now the next question is what happens there is energy loss. So, every little switching cycle now on this fundamental cycle of 360 degree you will have several switching cycles say something like every degree every two degrees or something like that for a small things you may have a switching; I mean you have one cycle of switching.

So, is there energy lost in the device on account of switching? Yes, how much is the energy that is lost on a account of switching. Let us say we will take some choose some other colour than red because it is already red; would green be all right; yes let me take green. Now if you look at here, this current is 0. And therefore, the amount of energy that might be lost is 0 may not be 0 that may be a very small thing. So, let us say this is the energy lost somewhere here.

And for every value of current it is possible for you to find out how much is the energy lost and the energy lost would might rise like this. So, this might be the relationship. Let us say for this value of current the energy loss is like this, this here and for the operating conditions it may (Refer Time: 31:24) that. So, the energy lost might actually go like this, it might actually vary like this and might come to something of this nature. So, what is it that I have plotted? I have plotted the switching energy loss you can say that this is E on plus E off; you can say this is E on plus E off I am sorry its a little unclear, let me check if I can.

So, during a turn-on it is going to have certain loss which is call as E on and during the turn-off it is going to have certain loss which you would call as E off. So, this sum of E on plus E off is like in one switching cycle, so but that let us say varies like this now. What will happen again here? It will be the same thing; the current may be reverse, but if the current reverse means what. Here one transistor and other diode are conducting here the other pair of transistor and diode will if top transistor and bottom diode conduct here the bottom transistor and the top diode will conduct here; so it does not matter. So, how would the E on E off vary? This will again vary something like this. This be could again vary something like that.

So, this is how the nature of variation of E on and E off is going to be. So, how is this variation? You can say it could be roughly sinusoidal if you ignore certain things if you say that this is proportional to the current now. So, you have certain average value, you can evaluate certain average value; then this is the average value you would take it as the average switching energy loss and multiply it with the switching frequency to calculate your switching loss the power that is lost here now.

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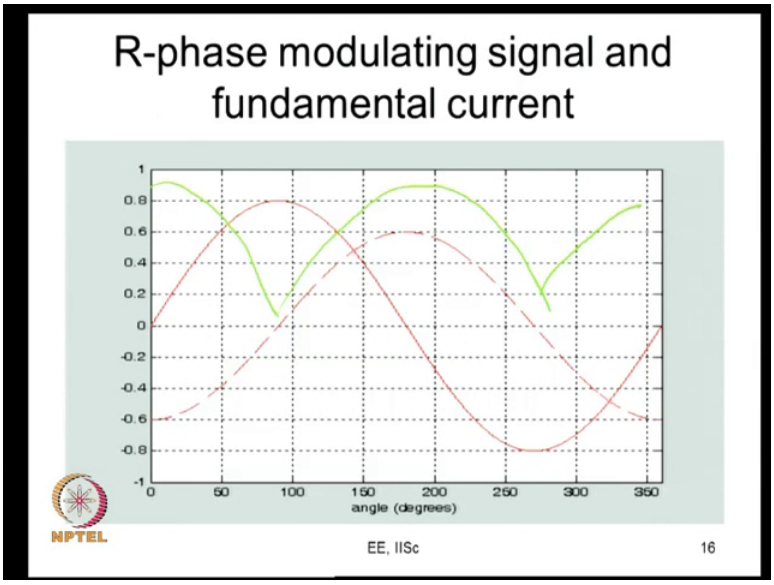

So, what we have going to now look at is; the same sin triangle PWM, but I am looking at a different power factor. So, if you see the power factor is something like 45 degrees lagging here and here the power factor is almost 90 degrees. When the phase is at its voltage is at its peak the current is at 0 now.

So, what happens to my loss? You see, there is certain amount of loss, what they said is the energy loss it is the DC bus voltage; it is not the fundamental phase voltage, it is the DC bus voltage. If the DC bus voltage is always the same throughout. So, once again what you will have here is you will have the same kind of energy loss, you will have the similar kind of energy loss that is just a phase shift here; you will have this would be your nature of energy loss. So, if you look at the difference between here and the previous one. So, you look at this and that there is no difference, the only there is a difference in phase otherwise there is no difference.

So, there is the variation of where the switching energy losses quite similar and its average value will be equal. So, what is it mean? What is the difference between here and there? It is the load the load current is same, but the power factor is different. So, even if the power factor changes you can say that the switching loss does not change significantly. If you are looking at sinusoidal PWM first we are looking at sin triangle PWM.

So, there is load now, the average value depends on what, it certainly depends on this peak value. What does this peak energy loss depend on? It depends on the peak current. So, the peak current goes up then this will also go up its average value will go up. So, the switching energy loss certainly depends on the peak value of load current; that is very clear and you know it is quite common sense. So, it is like that.

That it does not depend on the modulation index; that is are very interesting aspect. Well, it might indirectly depend in the sense that this modulation index determines the output voltage and that determines the current. But, it is a function of current, it is a function of the DC bus voltage and it is not a function of power factor. So, you can seen that for different power factors the average value is unchanged now. This is for sin triangle PWM and this is actually true for any continuous PWM, you can add third harmonic injection that is any continuous PWM where your signal is actually a modulating signal is a continuous function of time.

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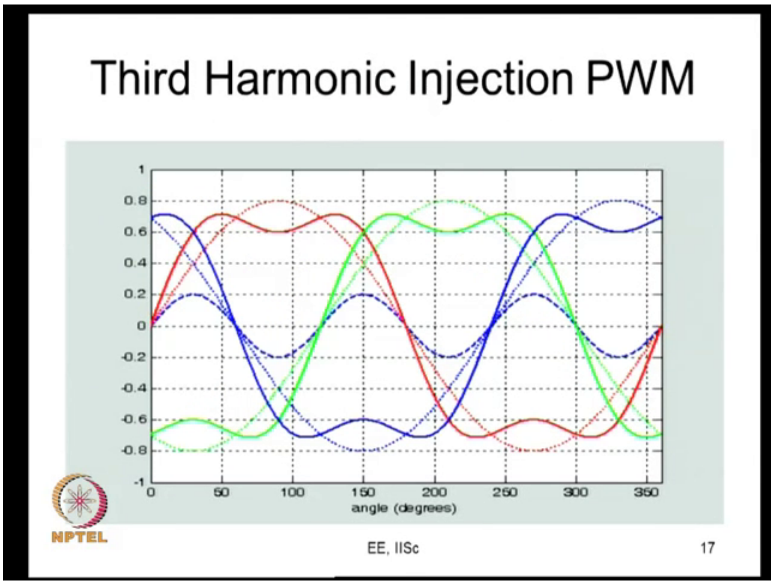

And example would be third harmonic injection.

So, here also what would matter is I am not shown the current here let us say the current is same as what you have here. So, that would mean the current would actually have 0 crossing will go like this; 0 crossing at the peak of the fundamental voltage and it will go like this. And at this here it will have its peak now. If you have the same current and this is same, so here also it is 0.8 the fundamental voltage is 0.8 here also the fundamental even the modulation index is 0.8, but here you have just added a common mode component. So, it does not matter. So, the fundamental voltage applied is still the same. So, the same load it might carry the same current. So, let us say it was 0.6 per unit was the current as we saw last time which is same current. And so the switching loss will be the same as what you get here.

So, the switching loss does not change when you go from let us say sin triangle PWM to third harmonic injection, whereas conduction loss changes. Conduction loss changes because it depends upon the duty ratio of the switches and the duty ratio depends upon actual modulating signal. Whereas, switching loss it largely depends upon the current, it depends on the DC bus voltage and the current. So, its amplitude and the power factor of the current. Again interestingly for continuous PWM methods it does not depend on the power factor also, it largely depends on the current. So, it is DC bus voltage and the current are the main parameters here.

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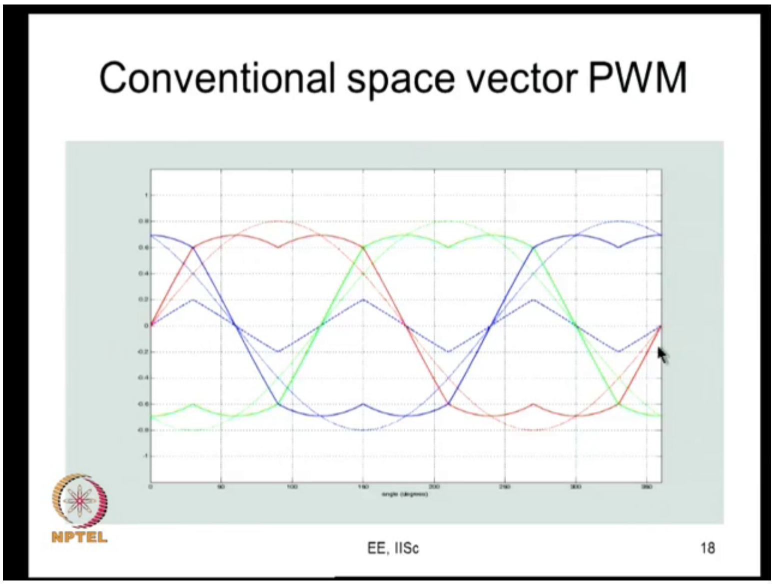

Now instead of that there is this conventional space vector PWM. You are not adding a third harmonic, but you are adding this 50 percent of the middle value of the sinusoid here. So, you are adding a common mode like this which looks like a triangular career and if you add that your r phase modulating signal looks like this. So, when you do this and do your triangle comparison and do your PWM generation what happens, your zero vector time gets equally divided; that is what we have seen before.

So, here also what happens let us say the same 0.8. So, the fundamental voltage is same, so if the same amount of current is applied as before I mean the load current is same as before you will send the switching losses same. So, whether it is sin triangle PWM or third harmonic injection PWM or conventional space vector PWM the switching loss is not different at a particular operating condition.

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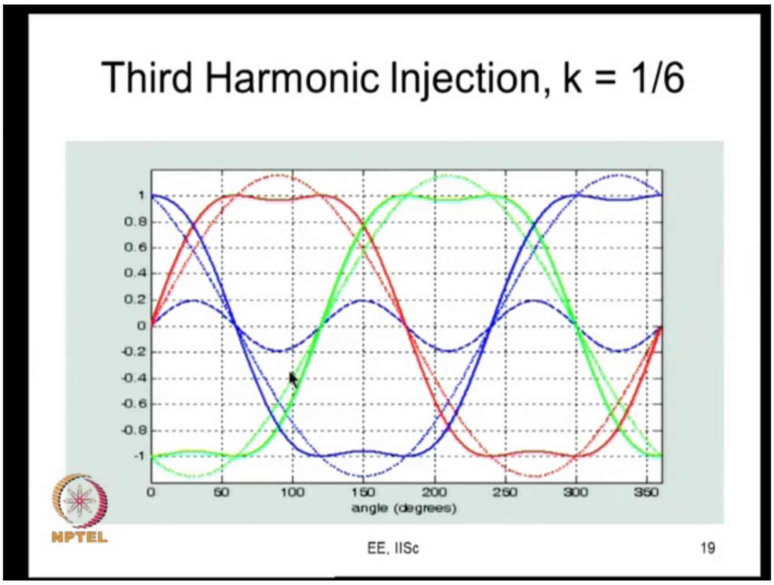

And it also does not change with modulation index.

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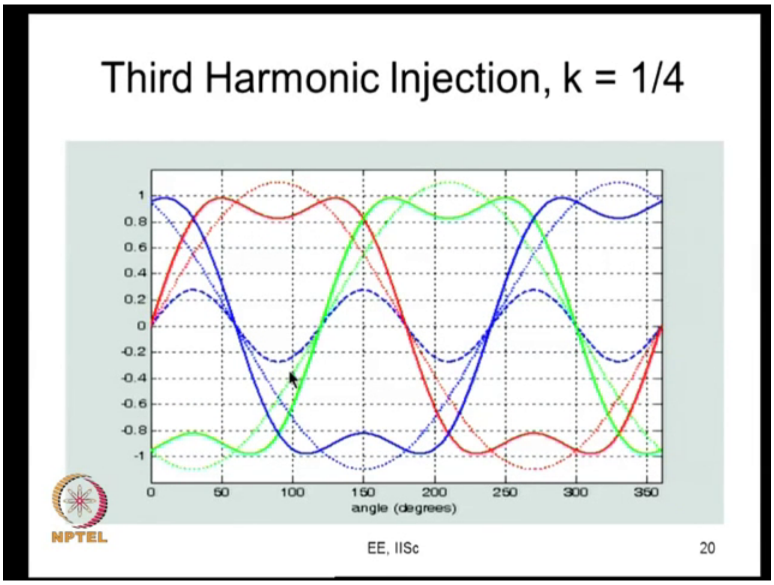

So, this is again third harmonic injection with where the harmonic amplitude is third harmonic amplitude is one-sixth of fundamental, here the harmonic amplitude is one-fourth of the fundamental, fine.

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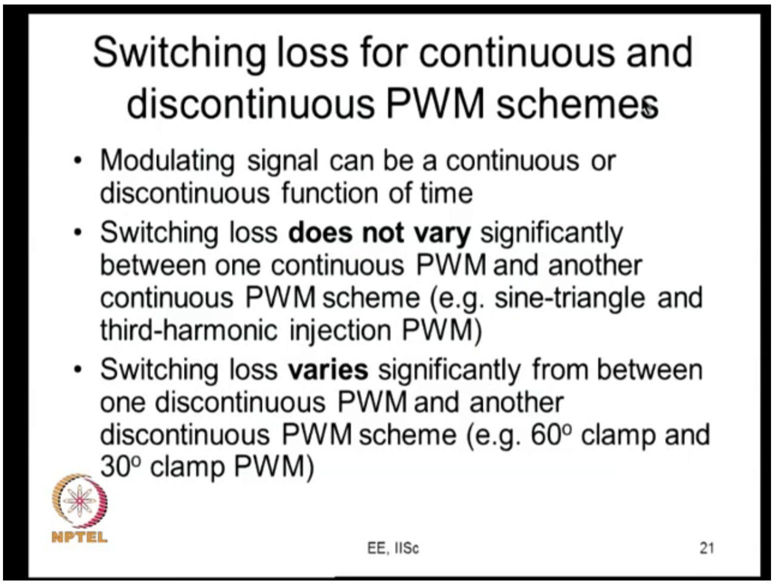

So, let us say that modulating signals. Now from continuously it is going to discontinuous PWM. In case of continuous the modulating signal is a continuous function of time otherwise it could be discontinuous function of time. As you have seen before switching loss does not vary significantly between one continuous PWM and another continuous PWM scheme: example sin triangle PWM and third harmonic injection PWM. This is what we just saw while back.

However, if you are considering discontinuous PWM; for example 60 degree clamp PWM and 30 degree clamp PWM. The switching loss would vary significantly between these methods. So, under the same operating condition 60 degree clamp would give you some switching loss, 30 degree clamp would give some other switching loss.

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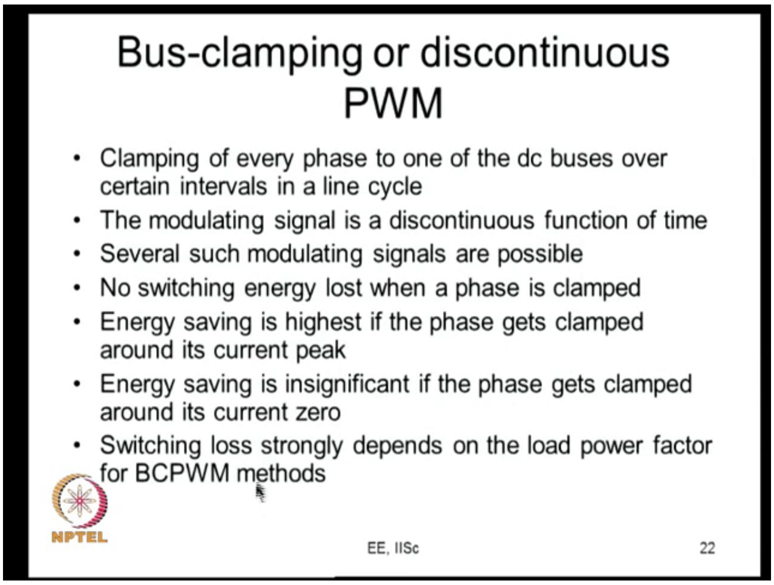

Why so? See, because bus clamping PWM what they do is they clamp every phase to one of the DC buses over certain intervals, which interval, which phase that changes from PWM method to a PWM method. For example, 60 degree clamp would clamp every phase in the middle 60 degree duration of its voltage half cycle of its voltage. 30 degree clamp would clamp every phase during the middle 30 degree duration in every quarter cycle. So, where it clamps changes now and the modulating signal is a discontinuous function of time which we have already seen, several such modulating signals are possible. And these modulating signals result in clamping over different durations

No switching energy is lost when a phases clamped. Obviously, because if it does not switch, whereas the energy switching energy loss nothing. And so, there is certain amount of energy saved now there is conduction loss, but there is no switching loss when it is clamped. So, how much energy saved on account of this you know by not switching? Energy saving has highest if the phase gets clamped around its current peak, if there is a particular phase. If the PWM ensures that the phase gets clamped when the phase is carrying its peak current, the current through a phase vary sinusoidly whenever the current goes through its peak the fundamental current if is a phase gets clamped then the energy saving is highest.

The energy saving is insignificant if the phase gets clamped around its current zero. So, phase current goes through zero, when it is crossing zero if you clamp a particular phase the energy that you are going to save is insignificant. So, switching loss you can see strongly depends on the load power factor for the PWM methods. For the same let us say 60 degree clamp PWM method. If the power factor changes so this is going to change; whether you are going to clamp a phase closer to its current peak are clamped closer to the current zero is going to change, and therefore it changes. And you can now readily see that the switching loss depends on the load power factor for BCPWM methods unlike the CSPWM methods.

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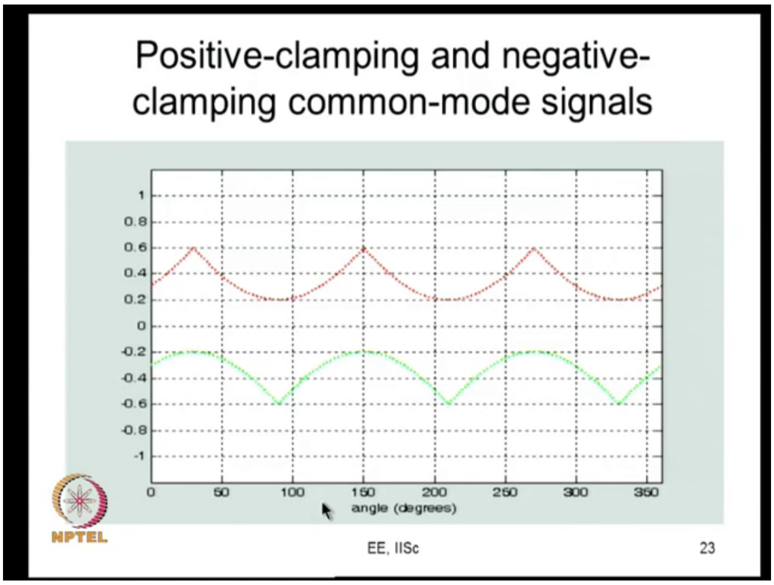

So, the different PWM methods the bus clamping PWM method there on account of these common mode signals. There are only two common mode signals that you can actually consider for clamping one of the phases. So, this would clamp one of the phases to the positive bus this would clamp one of the phases to the negative bus. So, you call them positive clamping and negative clamping common mode signals.

So, what you would normally do? As we have seen is follow this for some 60 degrees and another 60 degrees; so for 60 and 60. So, which 60 is the only question; you can follow this from 0 to 60, 60 to 120, 120 to 180 or you can follow this 30 to 90 here 90 to 150 and so on and so forth. That leads to different kinds of bus clamping PWM methods.

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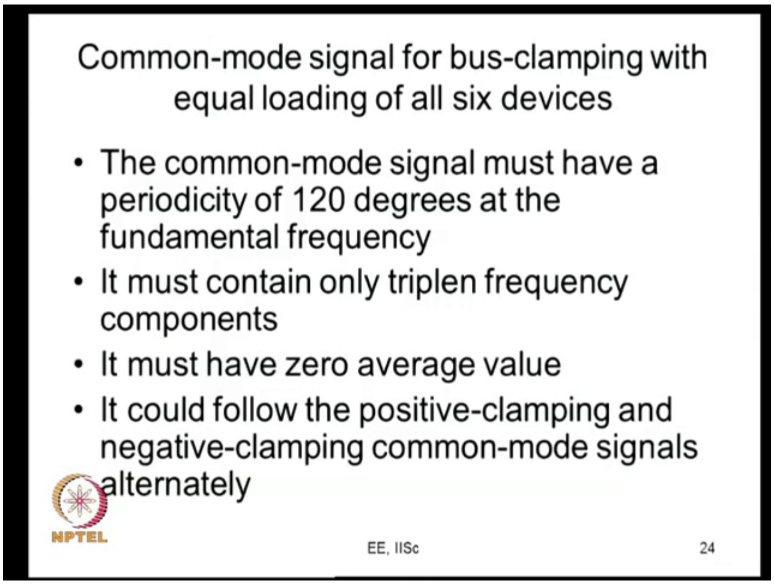

This is something which we have seen before. Must have a periodicity of 120 degrees and it must contain only triplen frequency component it must have zero average value. If you ensure all these things you will be making sure that the positive and negative clamping mode signals alternatively; I mean the whole operation is symmetric and all the six devices will have equal amount of losses we discuss this when we are discussing the PWM now.

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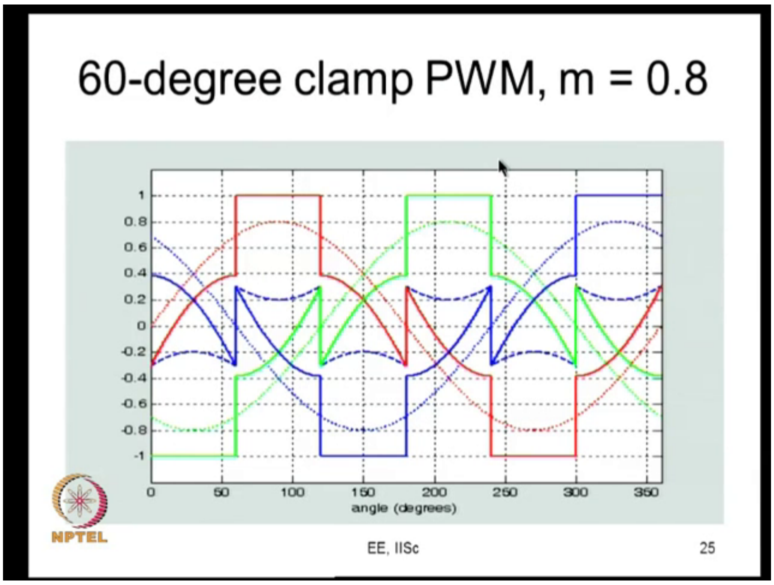

So, let us take this specific example of 60 degree clamping PWM method, because it is actually clamps for 60 degrees and it clamps a 60 degrees around the positive peak of the fundamental voltage. Again here it is the negative peak of the fundamental voltage here also it clamps for middle 60 degree. So, that is why it is called 60 degree clamp, it is just a nomenclature. In some papers you would find this as d PWM 1 and you know d PWM 2, d PWM 3 etcetera are all names used now.

Here it is also for the same modulation index of 0.8. So, the sinusoidal signal is same as the sin triangle PWM etcetera we saw before, but then you are adding this kind of a common mode signal. And therefore your resultant modulating signal becomes like this ok

So, now how about the switching loss? Obviously, there cannot be any switching loss in this particular r phase because here r phase is clamped. So, here there cannot be any switching loss in y phase because it is clamped, here there cannot be any switching loss in b phase because it is clamped, ok.

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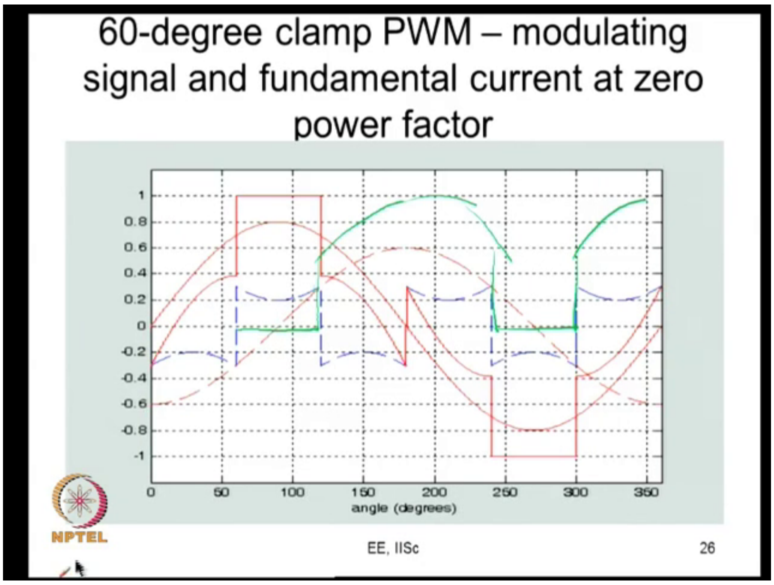

Now, what happens? How much energy saved that depends on what load power factors in and where exactly it is clamped. Now we have to taking a situation where you can see that the load current, this is the load current, this is 0 when the fundamental voltage is maximum. So, it you are looking at zero power factors. So, the current is actually going through 0 and you are clamping a particular phase.

So, what is a point? The energy that is lost on account of switching is very low here anyway because the current is very low. And therefore, by clamping r phase here there is going to be no significant amount of energy saved. So, the switching loss with this kind of PWM is going to be still quite high.

Now, instead of let us say the current is like this. So, let us also plot how that is going to look like. So, now the energy loss here will be zero; the energy lost here will be zero, how would the energy lost here will be that energy loss will be something like this; will go like that this is what r phase. So, once again the energy lost here will be 0. So, you will have the energy lost varying like this. This is how the energy loss would be and then the average value of this is now. So, the average value there is some reduction in the average value but that is not too high, because you have clamped only close to that now.

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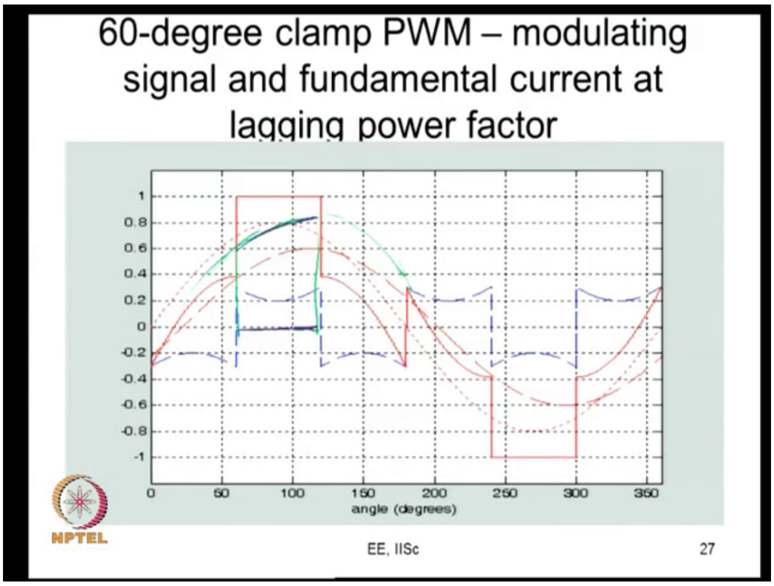

On the other hand let us say you go to something else some other power factor; it is a lagging power factor it is actually 15 degrees, but it is not too very lagging it certainly not 90 degrees. So, now what happens? You are once again you are clamping. So, when you are clamping this is 0. Your whole thing would have actually been, your whole the loss would have actually been like this. But now what happens to that? During this region your loss is reduced.

Let me draw this with a different colour maybe not here, not this one, so let us say here. So, what should have been so much is now reduced here; is now reduced. So, you get certain amount of savings in the switching energy, during this time you do not say. So, the switching loss of the same amplitude of current it is a different power factor the switching loss is no lower.

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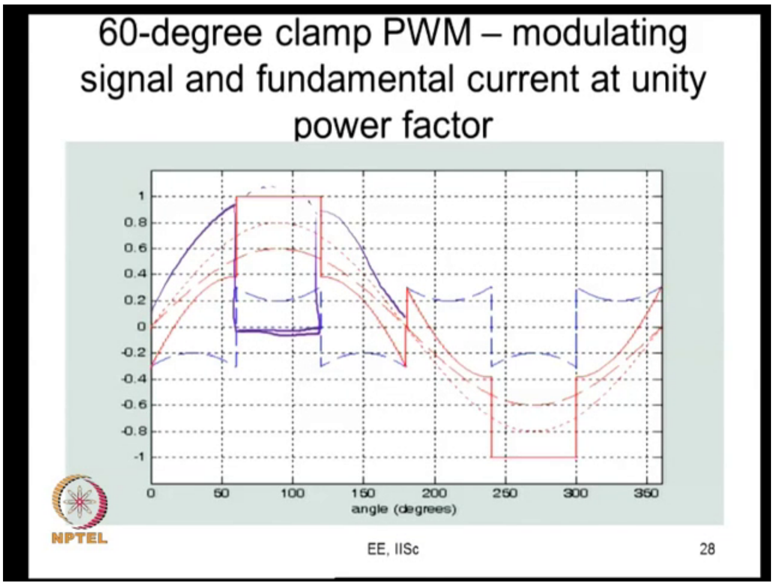

Now, look at this unity power factor case. Now the loss is 0 here and you would actually have your switching loss going like this, you might actually have it going like this. So, where the switching loss would have actually peaked this switching loss would have actually peaked here that you have avoided. So, you have saved a lot of switching energy in this region, you have saved a lot of switching energy in this region. And therefore, you have managed to reduce the switching loss. So, if our unity power factor the same amount of load current, but the power factor is no unity. You will see that the switching loss is low the switching loss will be lowest for 60 degree clamp PWM when you are looking at unity power factor.

So, as the power factor goes on reducing or the power factor angle goes on increasing the switching loss will also go on increasing. So, you can use the same E on and E off and you know here the energy lost is zero, because there are no switching. And you can calculate the average E on and E off and you can multiply that by the number of switching cycles that it has effectively had. And you can find out how exactly you now the exact switching loss can actually be calculated, because energy losses known to you this is how energy losses. And then you also know the switching frequency, how it is going to change here except that you have got account for this particular factor.

So, this is again the procedure there is a small modification in the way you calculate when you do a discontinuous PWM.

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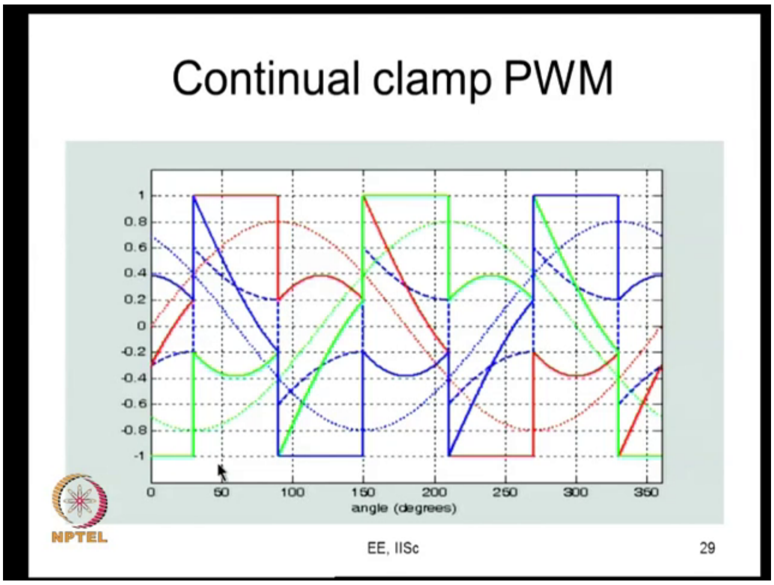

The same thing can be done for all this methods. So, during this region the switching energy lost in r phase IGBTs is low. So, you can now add that you can actually do this calculation for continual clamp PWM.

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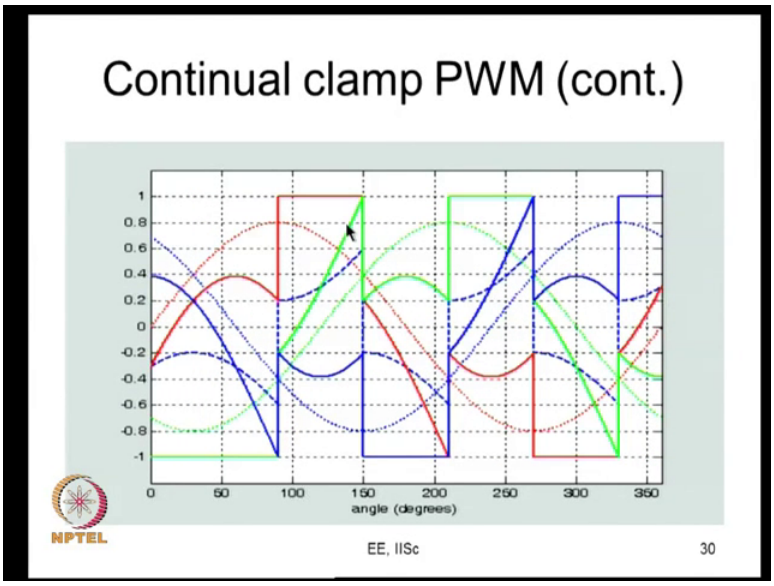

So, this is yet another continual clamp PWM. So, here also the procedure is very similar.

So, here you will see that this is good; the switching loss will be lower if the power factor is leading. So, if the power factor is leading let us say by 30 degrees this will give the best switching loss, will give you the lowest switching loss. So, at other power factor; power factor angles between 0 to 30 degree lag it is a reasonably. Lagging power factor angle this is a not a very good idea, whereas this is a very good idea for lagging power factor angles. For lagging power factor angle of 30 degrees this gives the lowest switching loss for a given current amplitude.

So, typically for an induction motor drive it might be a good idea to operate with such a continual clamp PWM method, because you know induction motor drives they operate at lower I mean some lagging power factor angle. So, it could be 30 degrees at full load something like 0.866 you have going to be very close to this. So, this is one generally for you know lagging power factor loads. This is a good thing to use now.

Whereas, this could be a good thing for leading power factor loads and this kind of 60 degree clamp could be a good PWM method for unity power factor loads from the point of view switching loss.

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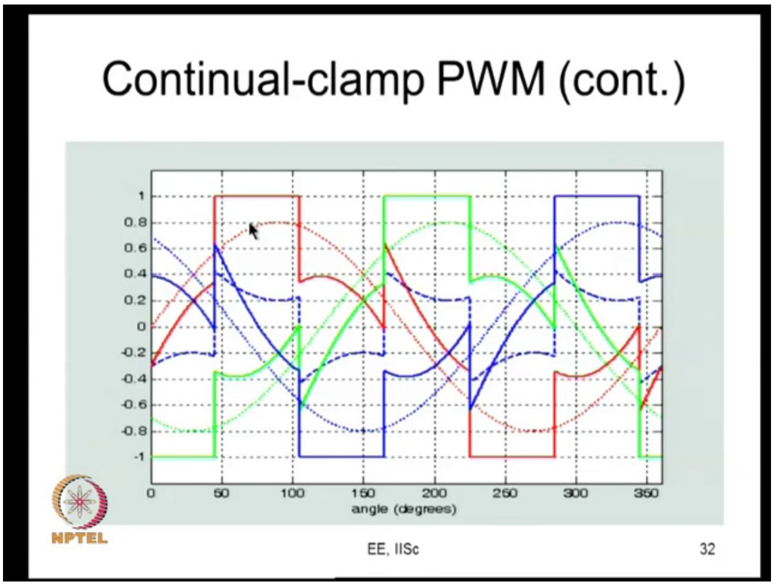

So, you these all it depends on depending actually on the power factor you can actually vary your PWM location now. So, if it is leading you can make sure that you can up to some point, as long as the load is lagging or leading and the angle is not more than 30 degree it is possible for you to clamp the phase exactly when its current is around it 0 crossing for 60 degree duration around a 0 crossing.

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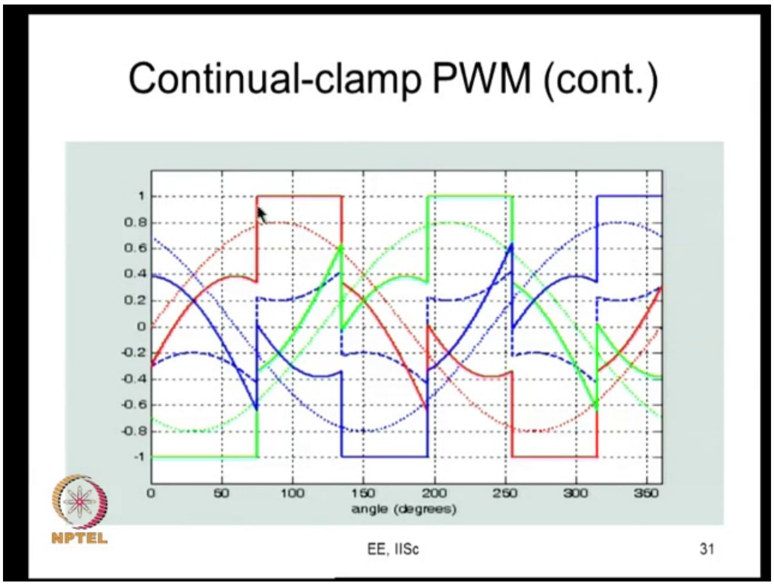

So, for example here, if you current is having its peak here you can clamp it I am sorry; you say you can clamp it around you know 30 degrees before and 30 degrees after the current peak, ok.

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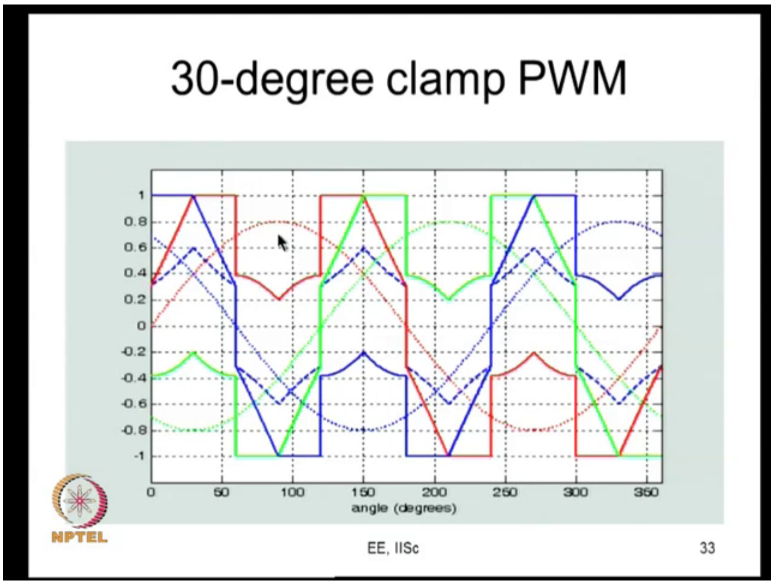

So this is actually good, when you actually go to 0 degree power factor. So, you what you can do is you will not be able to clamp a phase when it is carrying the highest current at 0 power factor why because, when the current is at its peak the voltage will be at it zero and when the voltage is at it zero you cannot clamp a phase. Because only a phase having this higher maximum modulation index or minimum modulation index can be clamped that m mid you know if you call this m max m mid and m min m min can be clamped are the phase corresponding m max can be claimed, but m mid can never be clamped.

So, you can never phase I mean you know clamp phase carrying the highest current at 0 power factor. But this is actually good idea for zero power factor. What will happen here is? You will find that the highest current carrying phase will not get clamped, but the second highest current carrying phase will get clamped and which is the best thing that you can do in this case.

So, for 30 degree clamp PWM also you can actually evaluate like, you have your E on E off available from the data sheet and the switching energy losses zero here, otherwise it is there and you know the number of switching cycles that it undergoes is known for you, therefore you can (Refer Time: 49:57) your energy loss.

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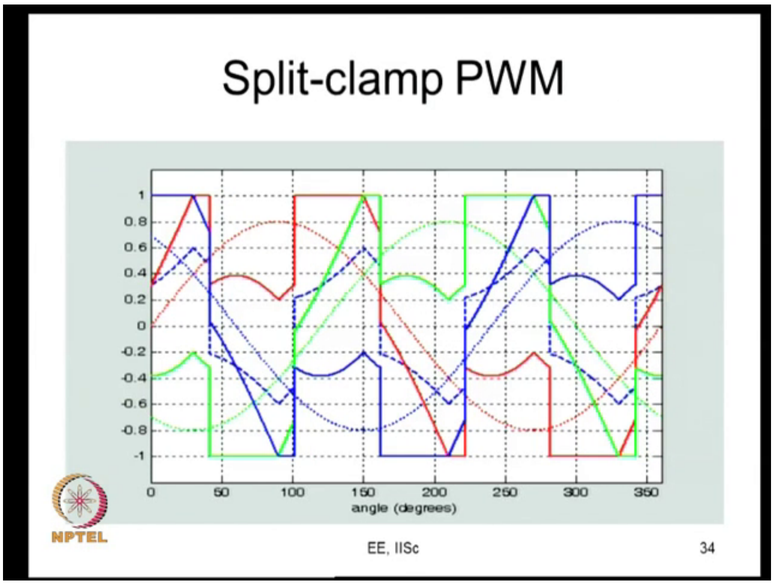

So, this is another variant of split clamp PWM, this will be good for some power factor angle between 60 and 90 degrees.

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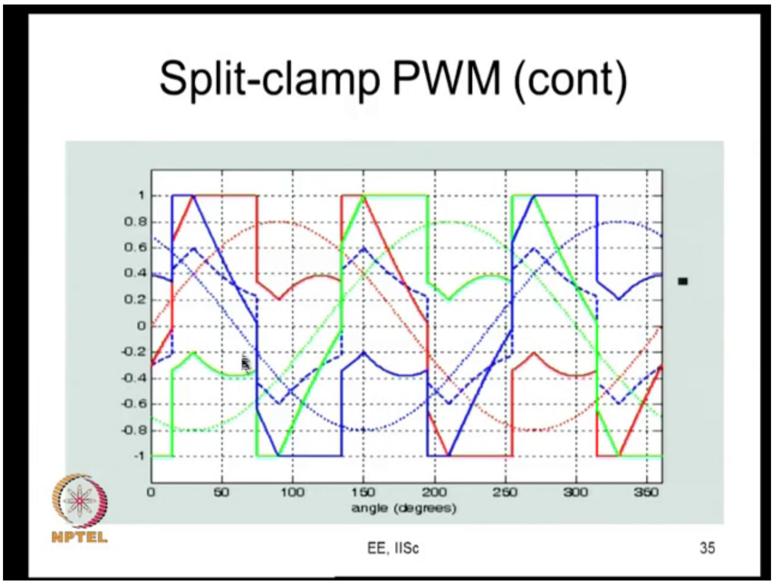

So, this is again for leading power factors between 60 and 90, it might be good.

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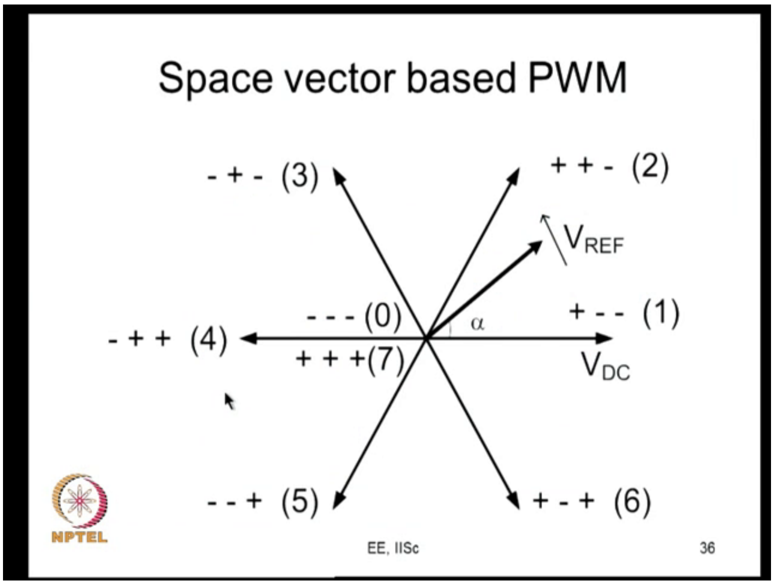

So, the same thing you can actually look at it from the space vector point of view, it is a revolving vector.

Now, what happens?

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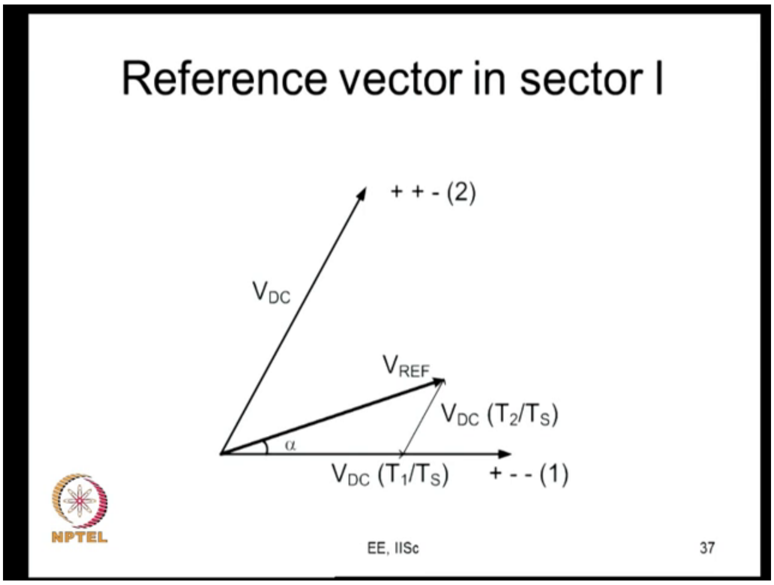

As we saw, we have going to apply vector 1, vector 1 and 0 for different times and we have going to realise vector.

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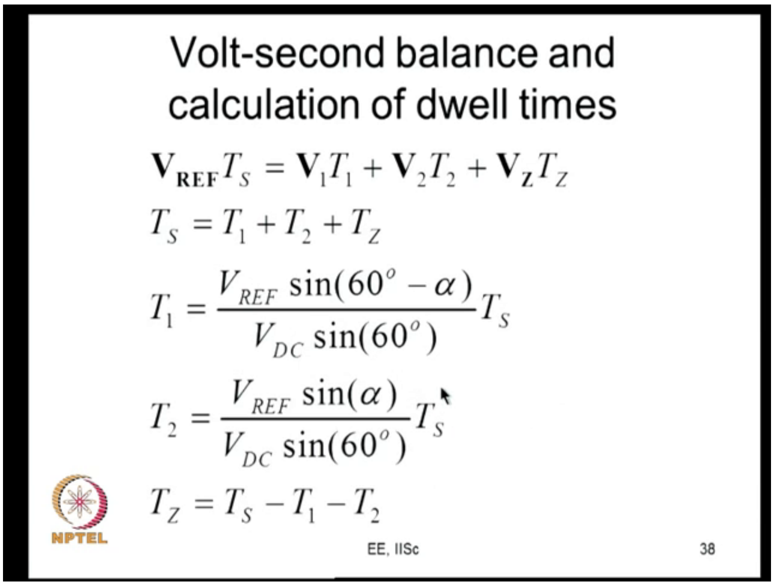

The difference comes in switching sequences. So, this is how we calculate all the times as we have discussed several times before.

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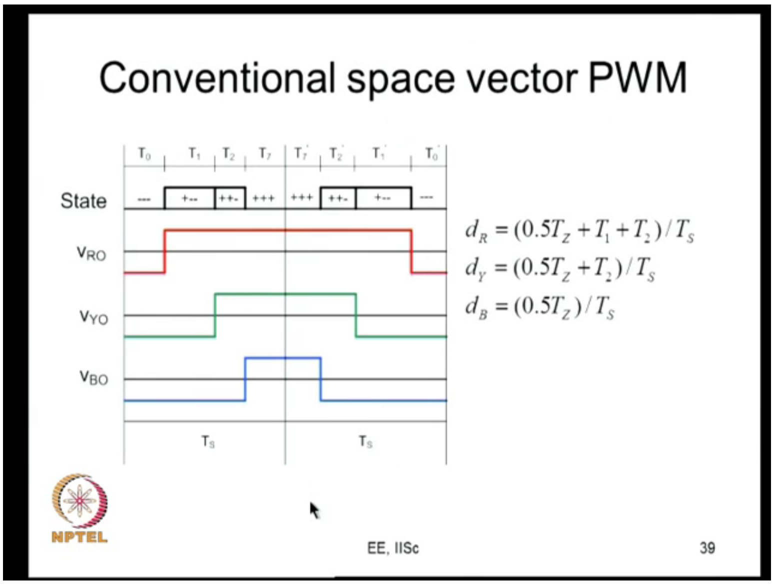

Now, we have going to apply this different states. Excuse me. Here what happens? R phase switches y phase switches b phase switch is 1, so all this there is certain amount of energy loss let us call this as er energy switching energy lost on account r phase this is ey, this eb; the total energy lost is er plus ey plus eb. And er is a function of the r phase current ir, ey is a function of y phase current iy, eb is a function of the b phase current ib.

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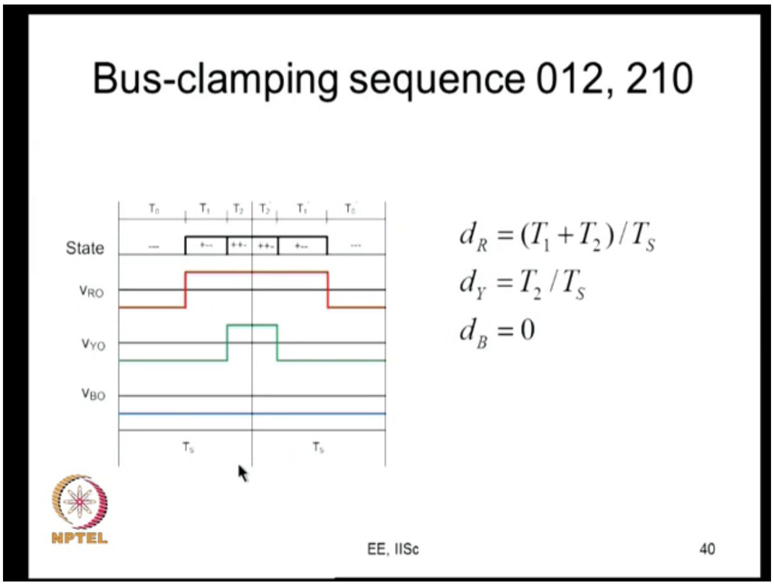

Now, if you go here the b phase is not switching. So, here what you have is only er plus ey. And again er is a function of ir, ey is a function of iy and eb there is no loss at all. So, you save certain amount of energy here. If this is when you are looking at as in the sub cycle by sub cycle bases, so it is only er plus ey; where er is the energy loss switching energy lost in r phase and ey is the switching energy lost in b phase; I mean y phase so er plus ey.

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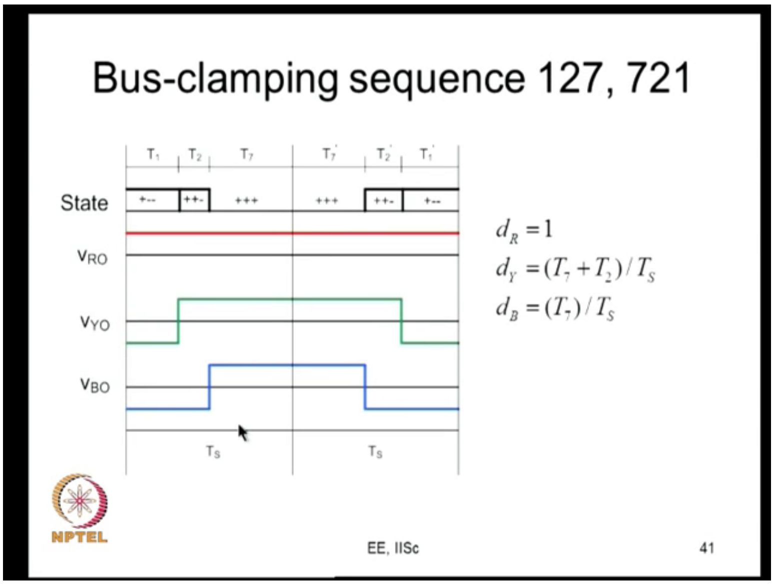

Same way r phase is clamped here. So, energy loss is only ey plus eb, and ey is a function of iy and eb is the function of ib.

So, if you are considering the same value of T S, these things will give you this bus clamping PWM schemes will give you lower value of switching loss than conventional space vector PWM; that is only if you consider the same value of T S. Normally, what you might do is you must reduce this T S to two-thirds of whatever its value for conventional. For conventional PWM if you have 100 microsecond you can have T S is equal to 67 microsecond for bus clamping PWM, so that both of them would switch at the same average switching frequency. You do this to improve your harmonic performance.

So, in that case you really need to work out and see whether there is an improvement or not. So, if you maintain the same T S then bus clamping PWM schemes are capable of reducing your loss by something like 30 percent to 50 percent switching loss compared to the conventional space vector PWM.

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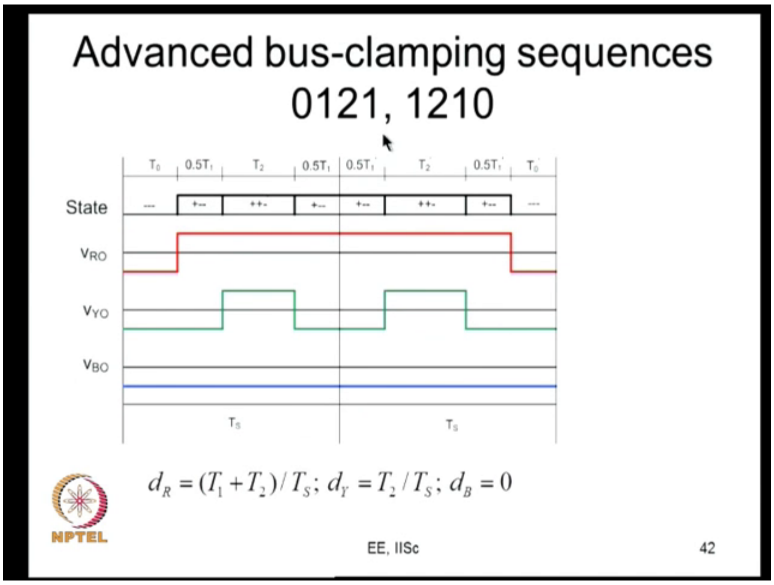

Here you have a different case. There is r phase switches, but y phase switch is twice b phase is clamped. So, what is a energy lost? The switching energy lost is er plus 2 ey, because this is you know the y phase current is not going to be significantly different between this instant and that instant. There is r phase current this er is the function of ir ey is a function of iy. So, it is er plus 2 ey is the energy lost in the sub cycle eb is equal to 0; is that a good is it does it have any advantage or a disadvantage it depends on whether ey is higher or eb is higher. In case eb is higher you are avoiding that switching and you are switching ey. Once if eb is greater than ey this is advantageous, if ey is greater than eb then this is a disadvantageous as simple as that.

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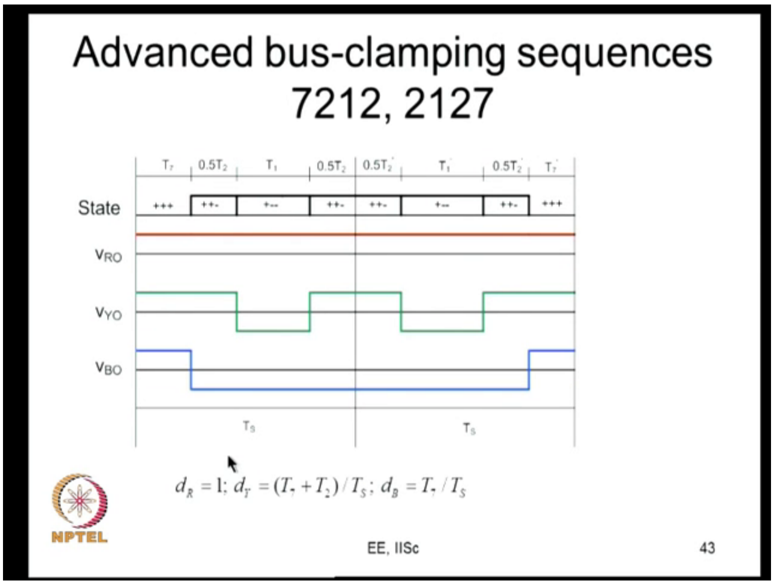

The same logic can be applied here for 7212. So, here what happens r is clamped, but y phase switches twice. If er that is a switching energy loss of r phase is greater than the switching energy loss of y phase. For example, r phase is close to its peak current r phase current, whereas y phase current is closed its current 0 then you will this is advantageous. If y phase current is greater than r phase current this may be a disadvantage.

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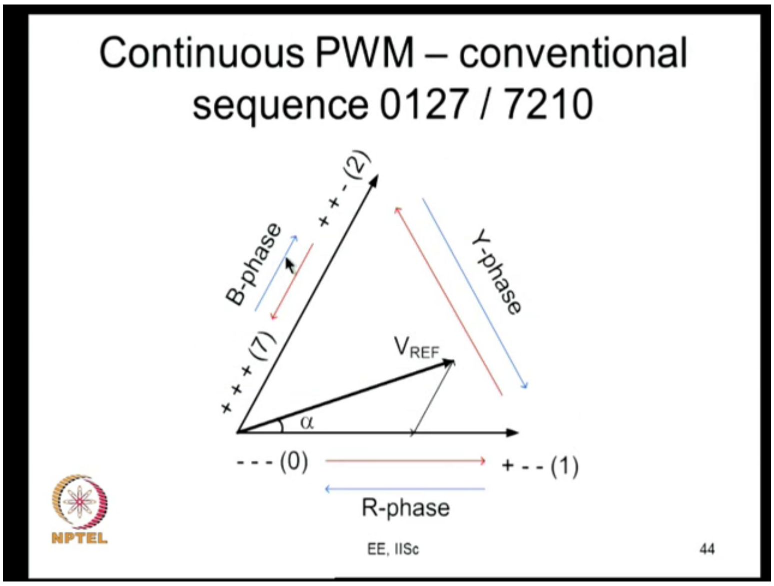

Now, this is the same thing where I have shown the sequences like this. If it is conventional you go around and you come back, this is the conventional space vector

PWM any continuous PWM. See continuous to the only difference is you know conventional space vector you stay here for 0.5 T Z T 1 T 2 and 0.5 T Z. In the other methods it may not be 0.5 T Z, it could be 0.2 T Z T 1 T 2 and 0.8 T Z; but does not matter, same number of switchings and the same amount of switching energy lost.

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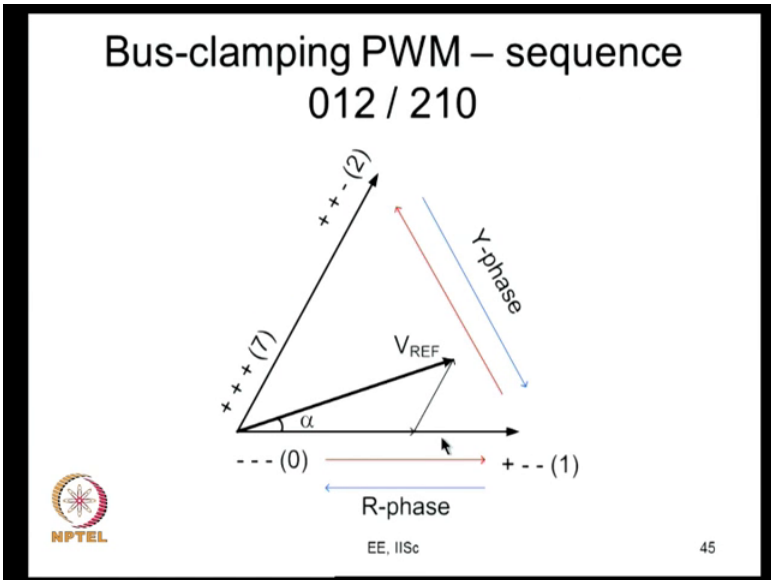

So, in the bus clamping; excuse me, you are avoiding this b phase switching which is what I mentioned before now. So, this you can now look at whether it is advantages or disadvantages if you know by clamping b phase; b phase is carrying high amount of current this could be actually an advantage.

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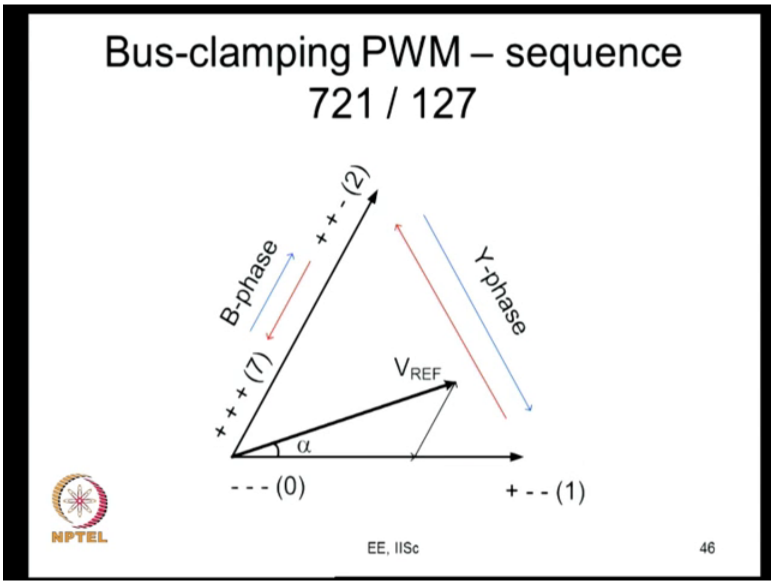

Now, here I have shown 721; 127 this is your switching like this is another bus clamping PWM sequence. If r phase carrying is a high current this would be advantageous.

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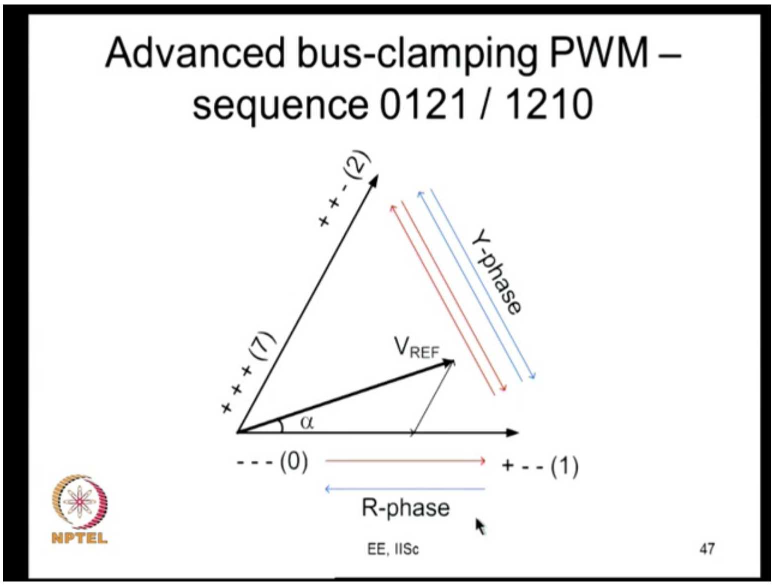

Now the 0121, once again would be an advantage if b phase carries higher current than y phase, because y phase there is going to be a double switching.

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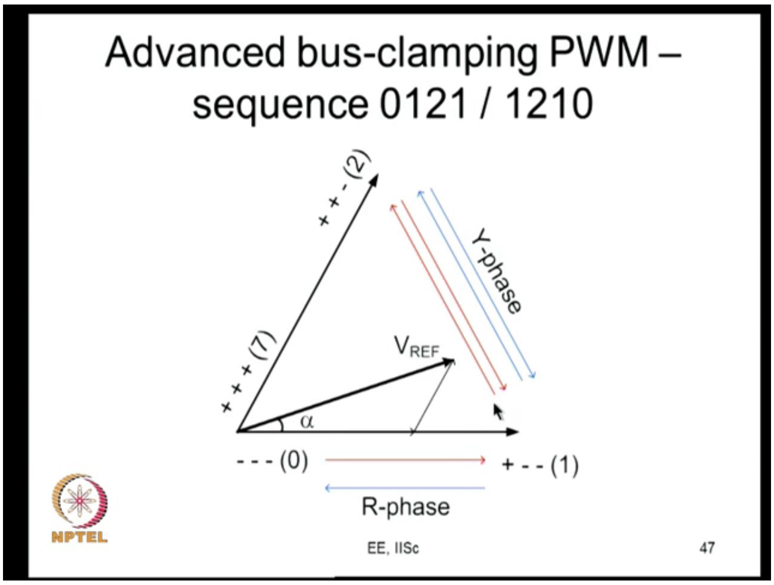

Similarly, you have 7212 and 2127. So, here again you have this situation where you will see that this is when r phase is not switched. So, when r phase carries a high current are the switching energy loss corresponding to r phase is high it is better not to switch r phase. And if for example, y phase has got the lower current this might really be an advantage to do that. That is one way of looking at it.

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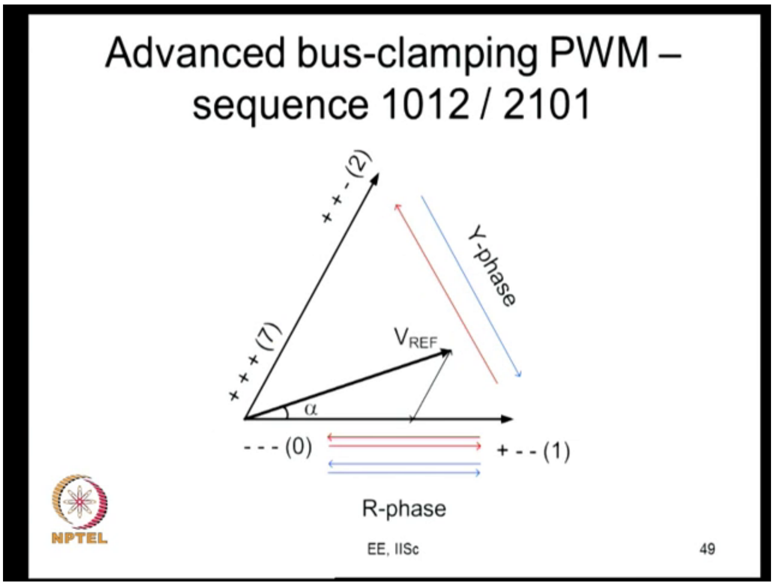

Then the same way you can look at the other sequences like 1012 2101. So, what happens? You start from one you stay here for T 1 by 2 seconds you go here and stay here for T Z, you come back and stay for T 1 by 2 seconds and go here and stay for T 2 seconds. So, you switch r phase twice from the switching loss point of view this is a good idea only when r phase carries low amount of current.

And particularly r phase should carry a current which is significantly lower than the current carried by b phase. So, you are going to avoid b phase you going to use r phase; double switch r phase.

Similarly, what you are going to look at is.

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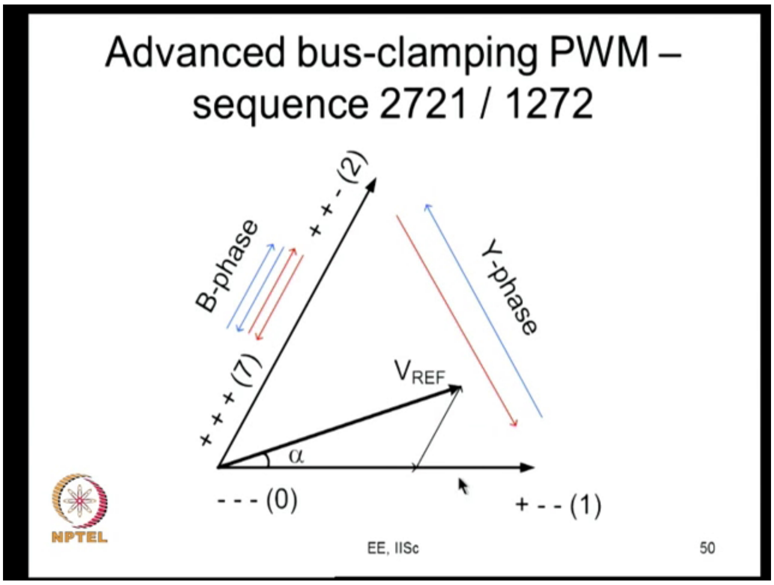

Here if you use for example, 2721 you are switching b phase twice. This is the advantages in a situation where r phase has no energy loss, whereas b phase I mean r phase is high amount of energy loss and b phase has got a lower amount of energy loss.

So, these various sequences are there for the same amount of v ref and you know depending upon the current. And you know that is essentially like the relative values of the currents of the three-phases they proved to be either an advantage or they proved to be disadvantage. So, you can always calculate. So, once you have the energy losses available you can also always calculate the switching loss for various PWM methods also.

So, what we will do?

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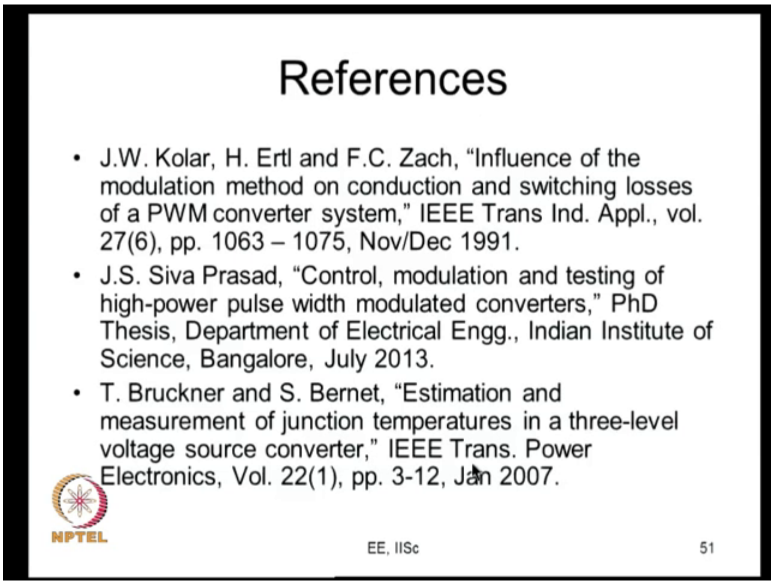

We will look at in the next class we will look at some design of PWM methods for low frequency; for reducing the switching loss.

So, here are some references which tell you how you can calculate the conduction and switching loss for some continuous and discontinuous PWM method. And here in this thesis a part of the thesis is about calculation of switching and conduction losses. So, this would actually give you some example of continuous PWM, discontinuous PWM, and an advanced bus clamping PWM also. And this is one other paper where you know the effect of all the losses about the rise in junction temperatures etcetera. So, such things are actually discussed here.

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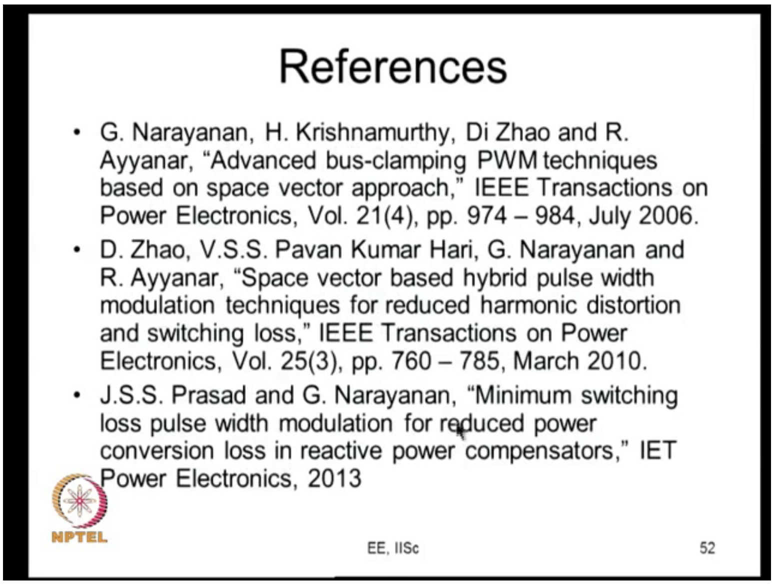

And these are some references where you actually have this advance bus clamping PWM methods. So, some of these contain switching I mean PWM methods which have an advantage of reducing the switching loss over the conventional methods at certain operator under certain operating conditions.

So, we will be discussing you know certain ideas from these methods in the next lecture which would be essentially on designing hybrid PWM or PWM methods for reduced switching loss. So, I thank you for your interest in this lecture series. I thank you I mean; I hope that this lecture was useful and look forward to your continued interest in the remaining lecturers.

Thank you very much.