Pulsewidth Modulation for Power Electronic Converters
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Lecture - 31
Evaluation of conduction loss in three-phase inverter

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

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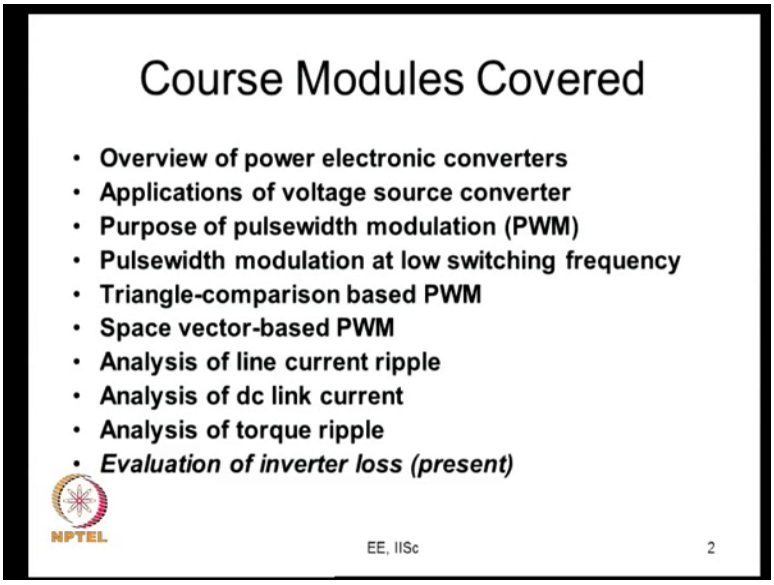

So, so far we have covered several modules in this course. One of the first modules we covered was on was on overview of power electronic converters. Different types of dc dc converters and dc ac converters; including voltage source and current source and multilevel converters, neutral point clamped converters, flying capacitor and so on. And then the second model was on applications of voltage source converter such as modern drive active front in rectifier, injective power compensation etcetera. Then we looked at some principles preliminaries of pulse with modulation.

Then we looked at generation of pulse with modulation at low switching frequency, how would you go about doing it. When there are few switching angles in fundamental cycle. So, we looked at things like selective harmonic elimination for example, and some offline optimal PWM.

Then we looked at this generation at higher frequencies; that is at this is triangle comparison, you compare some three-phase modulating signals with the carrier whose frequency is much higher than the modulating signals frequency, and you produce PWM forms. The same way you do it with a space vector, there is a revolving voltage vector given as a reference. You sample that every time and you use your inverter as a different vectors produced by the inverter, and make sure that the inverter produces an average vector which is equal to the reference vectors same thing done in space vector.

We where looked at what are the differences. We have seen that space vector based PWM is more general than that. Both continuous and discontinuous PWM methods can be implemented either using triangle comparison or space vectors, but the so called advance bus clamping PWM methods, are actually space vector based PWM method.

So, after the PWM generation, we are looking at the analysis. We were looking at the wave form quality. Primary thing in the wave form quality is like you know RMS current ripple. So, we looked at how to analyse the current ripple, in this space vector domain. Then we looked at the dc link current. So, how do you calculate the RMS dc link current and then from there the capacitor current? So, the RMS capacitor current as I mentioned is important for sizing the capacitor. Not only that that is an important input for evaluating the loss in an electrolytic capacitor.

So, in the electrolytic capacitors you have certain, you know some amount of loss happening which is represented by what is known as the equivalent series resistance ESR. So, once you know RMS current, you can square the RMS current and multiplied by ESR to get some measure of much loss could be expected inside the power you know, the electrolytic capacitor.

So, in some sense we have started on those things. Like, we know that for example, if you know the RMS line current ripple. So, you can find out what is the copper loss, in the series elements. For example, if there is a line inductor. The line inductor would have some internal resistance. So, this RMS square multiplied by that would be the additional copper loss on account of these harmonic currents. And this dc link current and from the dc link current you can evaluate the capacitor, current the RMS capacitor current gives you a measure of what is the capacitor loss.

So, we also analyse the torque ripple, which are related to the line current ripple. Now like you have a measure for the loss in the capacitor, you need losses in the other places; that is main things are losses in the semi conductor device so that what we are going to look today, or in this particular module; so evaluation of inverter loss.

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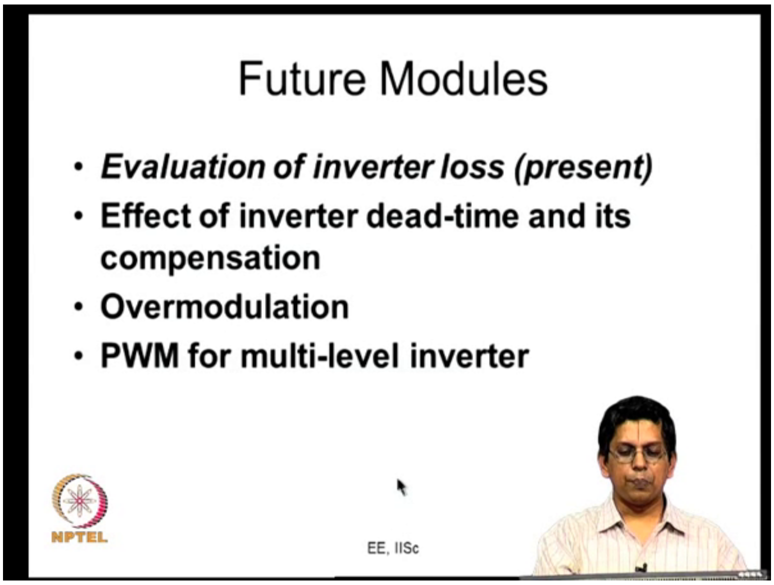

So, once we have done with the evaluation of inverter loss, up to this point we have actually been dealing with idealised inverter. We have not really looked at anything on you know the non ideality significantly. So, here is when we start looking at, the devices where regarded as an ideal device.

Now, we are going to say that we are going to look at start looking at the devices practical devices. So, practical devices will have certain amount of power drop, when they are on. And they will take finite amount of time to turn on and turn off they will have certain amount of switching energy loss and so on. So, we will try to calculate the conduction and the switching energy loss.

The further modules to come would be the effect of the inverter data. So, what is that? As I just mentioned practical devices take a finite amount of time to turn on and turn off. So, the devices in one leg are switched a complimentary fashion. So, one leg is turned one device is turned off, and the otherwise device is turned on.

Now, since there you know there is a small possibility that both of them would conduct concurrently. Because it takes some finite amount of time for the devices to turn on and turn off. So, what we do is we first turn off the device in one leg. The device which is to be turned off is turned off first, and then the next devices turned on. So, the gating signal to the incoming device is delayed by certain amount time which is called as dead time. And this dead time has an adverse effect on the invertor's output voltage waveform, and that is what we call as the dead time effect. And we talk how to compensate for that. So, from this point (Refer Time: 05:23) looking at non ideality.

So, one of the effects of the non ideality is inverter loss, and then you know other ways the dead time and effect of dead time. And here we would look at over modulation. So, so far, we are looking at situation, where the modulating signals peak value does not exceed the carrier peak. So, you will have a situation if the modulating signals peak exists carrier value look that is over modulation. So, we will look at over modulation. And then finally, we would look at few PWM methods for multilevel inverter. It should be the end of the course.

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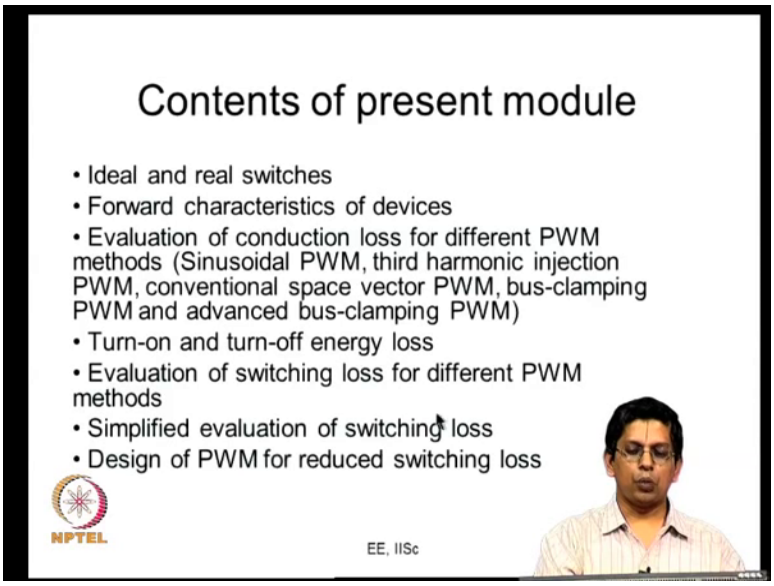

So now over to this today's module; what we going to look at is; we have going to look at ideal and real switches. So, all along we consider the switches to be ideal be. So, what do you mean by ideal? And what do you mean by real switches? What are the differences? So, one of the difference is in the forward characteristics, there is an amount of forward drop. So, we would we would look at how the forward drops of the day different devices can be modelled. Then we would try and see how to calculate conduction loss. Because in the forward drop is considerable the switch you know this ideal switch there is no loss, because when the current it is conducting the voltage is 0.

When it is off any way we know the current is 0, but in the practical switch when it is conducting there is a small forward drop. And therefore, there is a power loss. There is some voltage into current is non-0. So, there is some power loss, and that is what we call as you know conduction loss. So, we would try to evaluate this conduction loss, and as we can understand this conduction loss could vary with PWM method to PWM method.

So, we would quickly discuss this PWM method which we have of course, we have discussed before. We would try to see how the conduction loss would vary from one switching PWM method, or how to really go about calculating the conduction loss or the various PWM methods. Then we will look at the turn on energy loss and turn off energy loss, when the device is turning on or turning off, that is in one leg one device turns off and other device turns off. The certain amount of energy lost.

So, what is that we look at that in the thing this is most probably with we such things will get into the next class in greater detail? So, this class would focus this lecture would focus more on the conduction loss part. Then we would evaluate the switching loss for the various PWM methods, and we will come up with the simplified evaluation of switching loss.

And we will finally, present some design of PWM method, which will reduce the switching loss. That is, we look at some PWM methods which will know particularly we would locate this advanced bus clamping PWM methods, and see how switching loss can be reduced using this advanced bus clamping PWM compared to conventional space vector PWM. So now, we get started with the topic exact topic for today which is conduction loss in three-phase inverter now.

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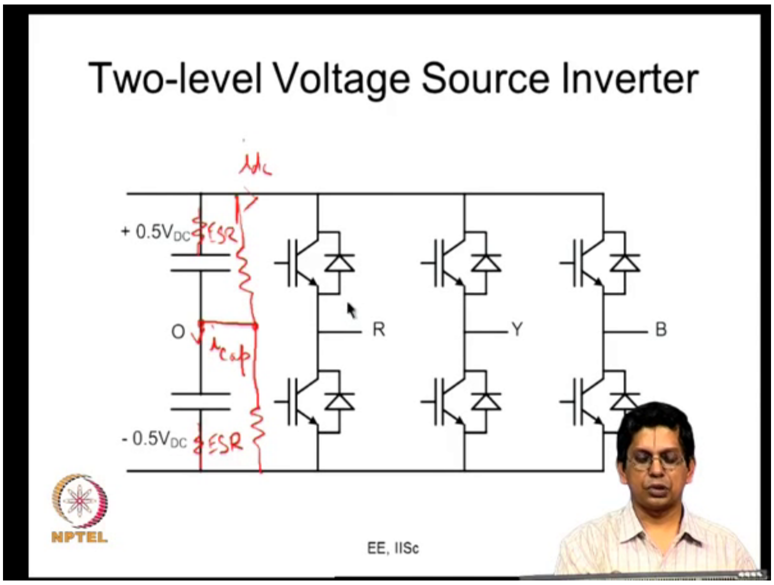

So, you have this, as I said all these days we will discuss them as ideal, and the last lecture we looked at evaluating the current through this. And once you now this current and once you know this current that is flowing from there it is possible for evaluate the capacitor current. So, the capacitors are often modelled like, you know the last class we did. So, we tried to calculate this current, what we call as idc and then we calculate this current i capacitor. So, if you look at the various sources or losses, you will see that you know for example, capacitors also there are losses, and that can be represented by what is called as ESR of the capacitor. So, you will have what is called as ESR of the capacitor.

So, whatever is the mean square capacitor current that multiplied by ESR would give you the amount of power that is lost in one particular in a capacitor. So, you can actually evaluate the losses in the capacitor. These further lead to temperature rises etc. There are capacitors models available, which can actually help you study how much temperature rise you know could be expected for given amount of power loss. In fact, from this power loss and temperature rise that are also you know some estimates for life time is also available, which are all available there in the literature for you. Now, but we not directly dealing with such things here. So, this is ESR. So, this is one component of the total power loss in inverter. There is another component of the power loss, that you may have in the inverter is, I just draw it in a maybe a different one or the same colour as fine.

So, there will not be a voltage balance here. So, what you normally do is you will have some resistors connected like this. Some resistors connected. What would be the purpose of these resistors? To balance out the voltage. So, there will be some amount of difference these 2 capacitance is we say this 0.5 V dc this is you know 0.5 V D c, may not be exactly so. So, if it is 600 volts, this is ideally should be 300 and 300. But this could be 320. This could be 280. As long as if it is small it does not matter, but if it becomes larger it is going to matter. So, what we do is we would look at you know we would try to make sure that. So, sometimes you may have the situation that one capacitor is higher voltage and the other one is lesser one. And therefore, you can eventually lead to kind of you know stress on particular capacitor and even damage of that capacitor.

So, we would ensure such kind of resistors, bleeder resistors they are called which make sure that there is certain amount of you know power sharing. So, the pow this serves the good purpose of ensuring that the voltage sharing between these 2 is very good. But then the bleeder resistors themselves will dissipate certain amount of power. So, if your total resistance is you call it as R B this is V D C. So, V dc square upon R B would be your power loss in the bleeder resistor. So, this power loss in the bleeder resistor is one component, and the power loss in the electrolytic capacitors itself is another component. So, these are some components that of losses the tool have here

Then, the major losses that actually occur are going to occur in these devices. So, the result of this losses is that there is going to be heating up the junction temperature is semiconductor inside would get heated up. So, if it gets heated up it would not function. So, we have to have an arrangement for dissipating all these heat. So, what is normally done is; you connect it on a heat sink. Every device is normally you never use this kind of devices without putting them on heat sinks. So, you may have large heat sinks. So, sometimes the devices maybe mounted simply on heat sinks. Sometimes they may be mounted on heat sinks, where you know with air blowed between the pins of them which is called a forced air cooling. So, this natural air cooling, this forced air cooling. So, you have certain cooling arrangements which will make sure that these think.

So, even with the cooling arrangements you have to make sure that, the device junction temperature does not cross something like 120-degree Celsius which is taken as the same junction temperature for many of these search devices, all right. So, we now look at, if you want to calculate what the junction temperature would be. Because you have to make sure that the junction temperature has gone to be low. So, you have to make sure that you know that the losses low: a low enough that it can be safely dissipated now. So, if the loss has to be low enough to be dissipated, you should know how to calculate the loss and the loss of these components of conduction loss and switching loss; which is what we have going to look at now.

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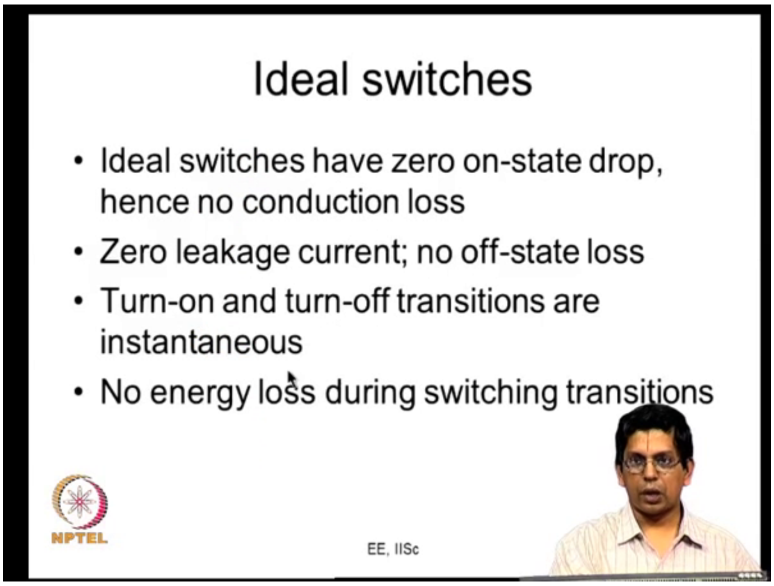

So, we have first ideal switches. Ideal switches have 0 on state drop and they have no conduction loss. Because when it is conducting the loss is 0, I mean that forward drop is 0. So, the product of voltage and current is 0 therefore, conduction loss is 0. So, when if you looking at the leakage current; that is in the off state is there current through the ideal device or practical device may have some small amount of current, what is called as leakage current and ideal device has no leakage current flowing through 0 leakage current. There is no off state loss. And when it switch turns on. An ideal switch turns on instantaneously. And similarly turns off instantaneously. And there is no energy loss. Maybe when it turns on or turns off, you know the voltage collapses immediately. And the current rises immediately, when it is turning on.

So, there is no instant when both voltage or current are high, concurrently and they does not have any significant energy loss during, there is no energy loss during switching transitions, this is in ideal switch.

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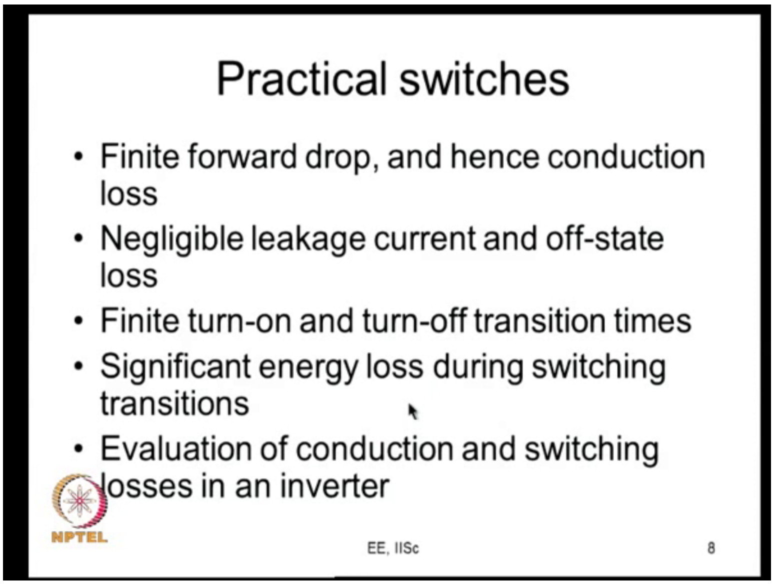

But you use devices like you know, MOSFETs, IGBT excreta; which are practical switches. They have a finite drop. So, you will have a drop across the drain and source term used in a MOSFET. The collector name (Refer Time: 14:03) used in an IGBT. So, you will have some drop. This drop multiplied by current is instantaneous power that is being dissipated in the device. And therefore, there is some something called conduction loss. So, this on state loss, the loss that is suffered by the device during the on state is what is termed as conduction loss. Thankfully when the device is off the leakage current is negligible. There may be some leakage current in a practical device, but it is negligible. And the off-state loss is also negligible. At least the off-state loss is too slow compared to the on-state loss, and the switching loss therefore, it is negligible.

But it takes a finite amount of time to turn on, as I mentioned a while back. And again, a finite amount of time to turns off. So, switching's are no longer instantaneous. And as it turns on, what do u you expect? You expect the voltage to fall, and then the current to rise. So, that the current would start rising before the voltage is fallen significantly. So, what will happen? At exact during this switching intervals, both the voltage and current are high concurrently. So, this leads to significant amount of energy loss. So, that is what you call as turn on energy loss. Similarly, when the device is turning off it takes finite amount of time.

So, during turning off what do you expect? You expect the current to fall and then the voltage to rise. Before the current has fallen the voltage rises. So, there is significant amount of both and V and I, V across the device and current through the device during such transition. So, that leads certain amount of power dissipation during that and there is an energy loss over the switching interval. So, you call that as you know switching energy loss and whatever. So, here significant amount of energy that is lost during turn on and turn off now. This is something which we might focus a little in the next class.

So, we are going to evaluate this conduction and switching loss in an inverter; that is our task now. So, if we can evaluate this we will know how much is the loss and then you can go about calculating what are to be done subsequently.

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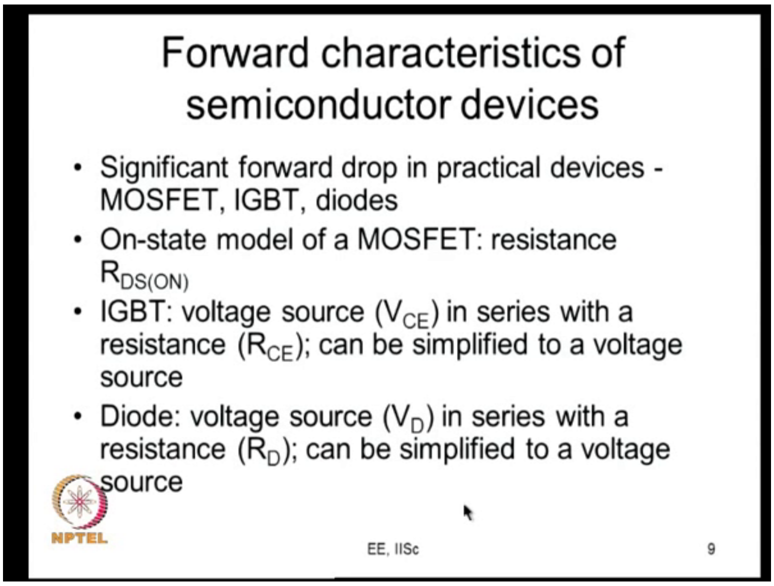

So, you have this, what are the go by individual devices, there is MOSFET there is IGBT there is diode. So, if the MOSFET is conducting, what is the relationship between the voltage across the MOSFET and the current through the MOSFET? That is what is called as forward characteristics; relationship between the forward voltage and the forward current that is when the device is conducting, what is the voltage drop? We see the current through the device.

In case of the MOSFET, the voltage across the MOSFET is proportional to the current through the MOSFET. And therefore, the MOSFET can be modelled as the resistance. It is as a resistance between it is drain and source terminals, during the instead and it is popularly represented by the symbol R DS on. R stands for resistance, this is a drain to source on is the on state. So, you call it as R DS on. So, MOSFET can be modelled by this value.

So, there is certain ratio of V by I V DS by I D and that is equal to this. If it is an IGBT, an IGBT is volt you know the forward characteristics can be modelled by you know you can consider the IGBT to be a voltage source V CE in series with the resistance R C. So, this can be a model for your you know IGBTs thing, but this can be simplified. For sake of simplicity, you can just simply consider it to be a voltage source say something like V c sat you can just call it, and you can consider it like this.

Similarly, for the diode you can consider when the diode is conducting, there is a drop. You would say point 7 volt you know; in power diodes it can be more than that. Like these are the anti-parallel diode for IGBTs, it can be 1 0.5 to 3 volts and so on, at higher current levels. So, you can represent this by some V D or actually V D in series with R D. So, for if you want it to be simple it can be simply be some voltage V D; so this voltage is will all be specified also in the data sheets.

For example, in an IGBT data sheet you will get this V CE. That is you will get it as a range. You would normally get the typical value; under certain conditions what would be the typical V CE would have been specified. And they would also specify what is called as the maximum V CE. So, we may get the same for the free willing diodes also, you may get the typical values and the maximum values. So, we can use this to common you know to calculate these losses as we go further.

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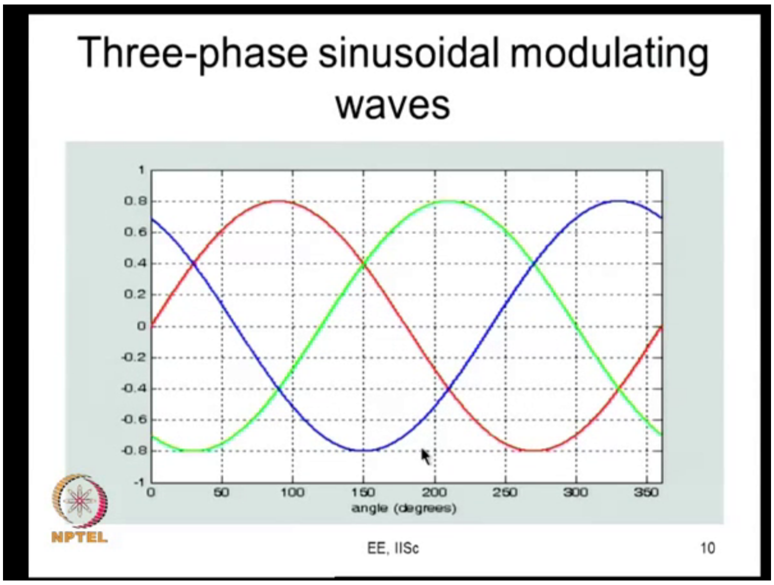

Now, that is about the voltage drop. Now we should know, how much is the current going to flow through? Etc. This is the voltage drop. So, which what current is going to flow through that it is the load current that is going to flow through the device. So, we need to understand what is the load current. Who determines the load current? It is the dc voltage and the modulating signals.

So, I am considering sinusoidal modulating signals there is; some voltage V dc, I am considering some sinusoidal modulating signal. Incidentally, it is 0.8. Like let us say one and minus 1 are the past even negative peak. So, the carrier it is 0.8 the modulation index is 0.8. The sign peak is 0.8 times the carrier peak here, alright. So, this 7 triangle PW, you have 3 of sinusoidal signals for R Y and B phases.

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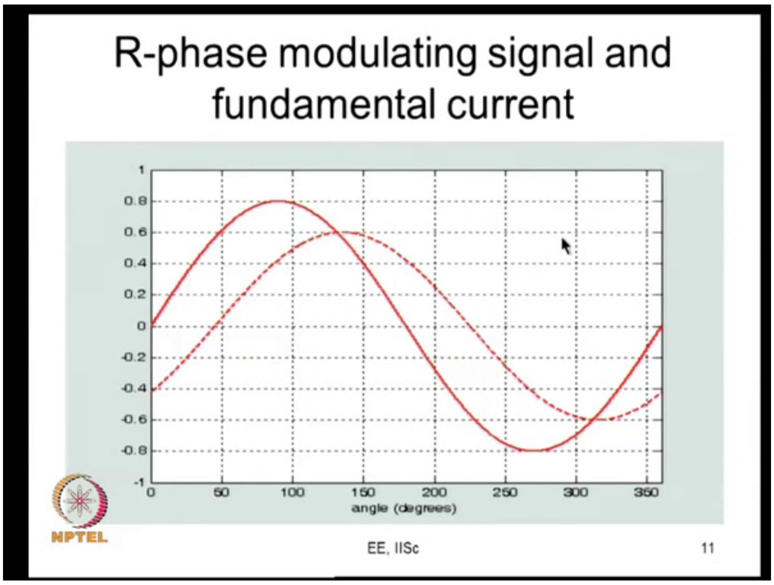

Now, you have some load. This is being fed to a load. So, this is, this represents the modulating signal actually represents the fundamental component of the voltage applied on the load or phase of the load. So, let us say the load is only inductive kind of the load or a load, I mean lying perfect load. In this case it is lagging by some 45 degrees a load consumes certain amount of current, which is given by this thing. Of course, the load will have certain amount of ripple on top of this current wave form, and we are just ignoring this and we only the fundamental current is shown here. And you can see the power factor angle is 45 degree the load is lagging I mean the current is lagging the voltage by some 45 degrees now.

So, if you look at who is conducting were you know this is R phase we are talking of R phase. So, R phase is got a top transistor top device. Bottom transistor bottom device, who conducts when depends on the direction of current? Now for example, the current is negative here the current becomes positive. Once again, the current goes negative. This determines which transistor or which diode conduct. Let us just look at it now.

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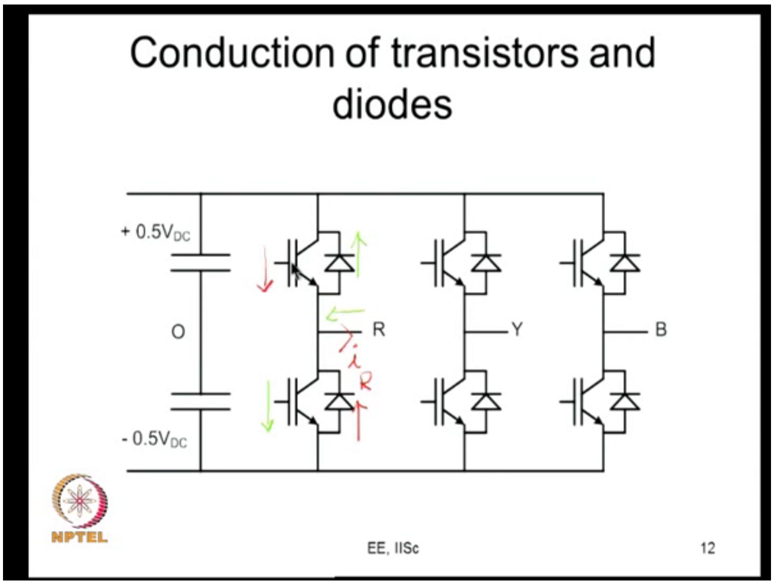

So, this is what I have for you here. This is a same voltage source inverter. So, let us say the load current i R flowing in this direction/ the load current i R is flowing in this direction. So, how will that flow through? It will flow through this, this transistor or it will flow through this diode. So, this top stop transistor, when your current is in this direction, this is only either that the transistor or the bottom diode will conduct. Sometimes the load current, let us call this as the positive direction of current. Sometimes load current could be negative. That is, it could be in the opposite direction.

Let me just mark that in a different colour. So, let us say this is the load current. So, who will conduct this load current? It is either the bottom transistor, or the top diode. This is these are the ones that will conduct this load current. So, it is always one pair of one transistor and one diode which transistor. And which diode whether top transistor and bottom diode or bottom transistor and top diode depends on the direction of current. That is what we trying to make sure here now. So, this is what I mentioned here. So, this is what we have now.

So, again weather this is the top transistor or bottom diode. That depends on what is the getting signal. If the modulating signal is greater than the carrier, then this is the top one. If the modulating signal is less than the carrier the bottom one that is what is illustrated here now.

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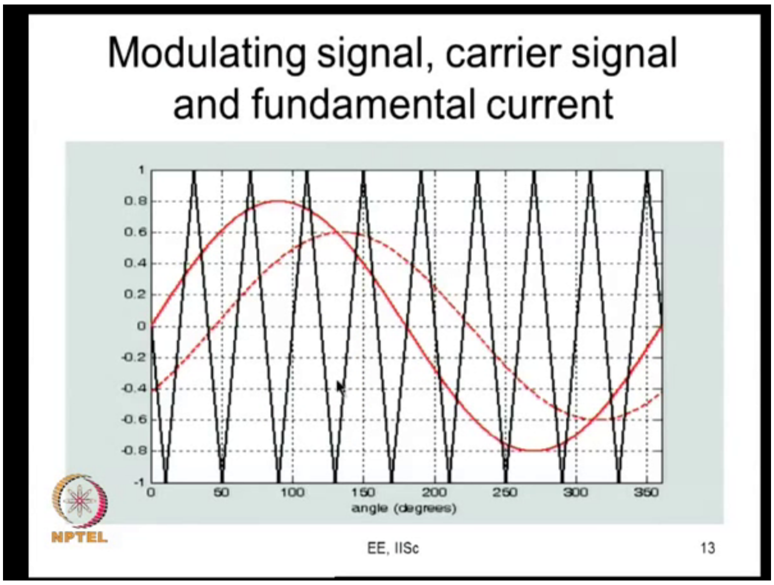

So, here you have the same R phase modulating signal and you have this R phase current shown here. And you have comparing it with the carrier. Of course, the carrier is shown to be of much lower frequency, in practice it could be a much higher frequency then this. So, whenever the modulating signal is greater than the carrier as we said in earlier lectures, this is going to be high PWM signal is going to be high. Therefore, you are going to have you know it is the top one will conduct. Again here, when the modulating signal is less than the carrier, the top getting signal will be low on the bottom getting signal will be high. So, it is the bottom transistor or diode will conduct, whether bottom transistor or a diode conducts depends on the direction of current. So, from these 2 combinations you know who is going to conduct well.

So, if the top transistor has been gated high and the current directions is this. Then this conducts. For the same direction of current, if the top transistor is gated low, and the bottom transistor is gated high then this, this cannot conduct this bottom diode conducts. The same way if you look at the green direction of current, now if the top transistor is gated high, and the bottom transistor is gated low, then this cannot conduct. So, the top diode will conduct.

On the other hand, if the bottom transistor is gated low. On the top transistor is gated high, then this current will flow to this diode. So, that is something first we need to know who conducts. So, only then we have to calculate because we need to next calculate the transistor drop, the diode drop and how much is that and so on so forth. So, let us look at it like this.

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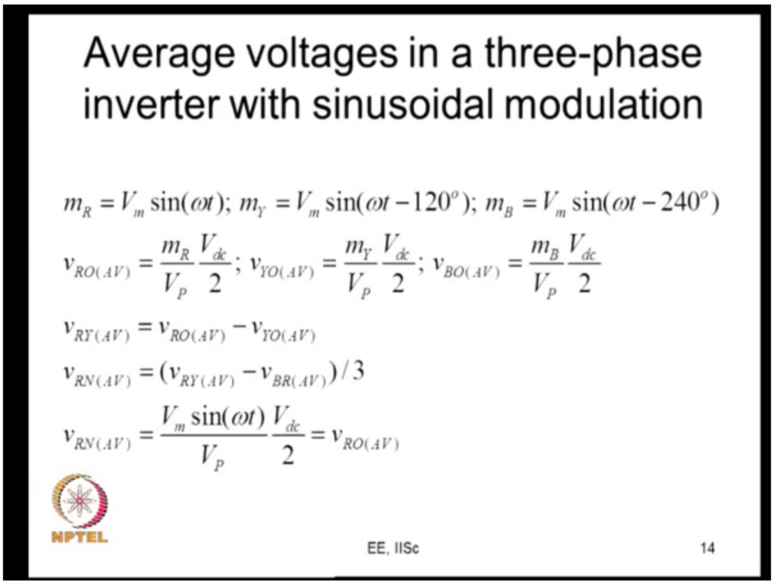

For now, if you go on it depends on the sinusoidal modulating signals. This is V m sin omega t V m sin omega t minus 120 V m sin omega t minus 240. So, these are average voltages which we have seen before. This is the average pole voltage. R is the midpoint of the like o is the dc midpoint. V RO is the is what as we call as pole voltage, V RO average is the average pole voltage. The pole voltage is being averaged over a carriers over a sub cycle of a half carrier cycle. And what is that equal to? It is equal to m R by V P times V dc by 2. If m R is equal to V P you can say it is V dc by 2, if m R is equal to minus V P you can say it is minus V dc by 2.

So, this can go between plus V dc by 2 and minus V dc by 2. This is the average R phase pole voltage, this is the average Y phase pole voltage this is the average B phase pole voltage. Now the average link line voltage is are V RO average minus V YO average; similarly, V Y B average, V B R average. So, then we are in average, if you consider balanced three-phase loads it is 1 by 3 times V RO a average minus V B R average. And you would look at V RN average, what it would be it would actually be this V RO average itself. This be V m sin omega t by V P into V dc by 2. In case V RO average has some common word, that common word would not appear in V RN average as we see now.

So, you have this kind of V RN voltage applied here. So, this voltages gets separate on the load and there is certain amount of current that is flowing through the load. And that current the power factor of that current also is important, the amplitude and the power factor of the current is important in determining your conduction as well as switching losses.

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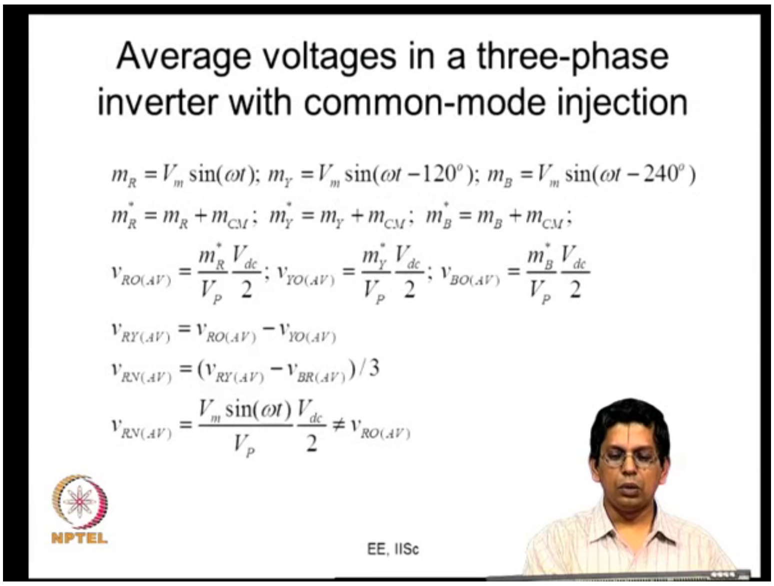

Now, if you take an example which is more general. Not just these three-phase sinisodial modulating signals, but there is also certain common mode component that is added what is called as m CM. So, it is m R plus m CM m Y plus m B plus m CM. This m R star m Y star and m B star are the actual modulating signals, you are comparing them with the carrier and you are producing these signals.

So, what is your V RO average? It is not m R by V p, it is m R star by V P into V dc by 2. The same way this is m V star by V P into V dc by 2. So, as we have seen before the advantage is that, V m can actually go higher. V m can go up to 2 by root 3 times V p. Normally V must be restricted to V P for sin triangle PMW. If you are adding common mode on up appropriate kind of common word then it is possible that V m can be has high as 2 by root 3 times V P that is 1.15 times V p. And even with the higher than that like 1 to 1.15 times V p, you can make sure that your m R star does not cross V p. So, you would get something m R star the peak value will not cross V p.

So, this increases the dc bus utilisation as we have seen before. And your V RO average V YO R Y and V RN expressions are given. Now you the difference you see is V RN average is V m sin omega t by V P into V dc by 2. Which corresponds to this, the m CM is gone there. So, it is not exactly equal to V RO average. So, whatever is the common mode component are the triple m frequency component in V RO average. They are been not off. And that is what you get in the V RN average. So, many of these PWM things are like third harmonic injection conventional space vector PWM bus clamping PWM, all these are you know there are different values of m CM are added in all this.

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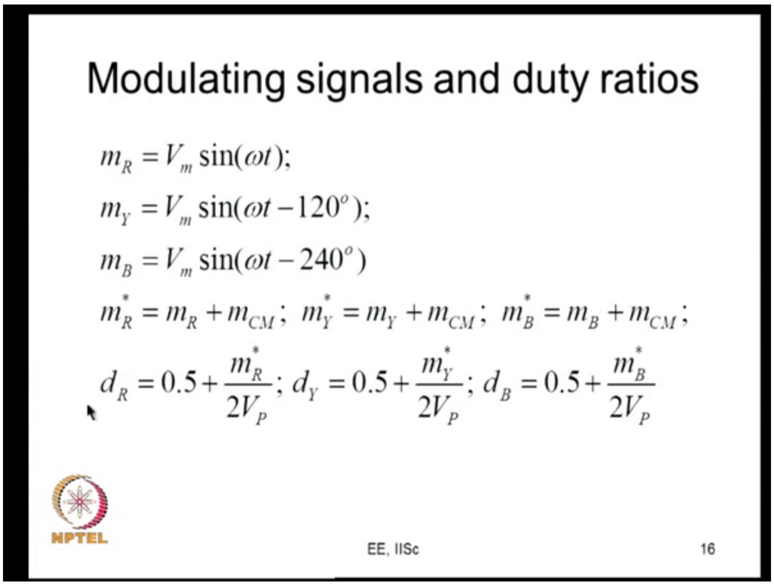

So, this is just a quick recap of what is being done here. Now we have to look at closely at the loss. So, for that you need the duty ratios of the different phases as we will see shortly. So, this is your R phase modulating signal, Y phase and B phase, and once again considering three-phase sinusoidal signals. Then I am adding common mode there. So, what is my duty ratio of R phase? It is 0.5 plus m R star by 2 V p. Let us say m R star is equal to V p, then m R star by 2 V P is 0.5. 0.5, 0.5 is 1. Let us say if m R star, let us say m R star is 0. In that case D R is 0.5. Let us say m R star is minus V p, in that case this is 0.

So, for m R star going between minus V P to plus V P D R goes between 0 and 1. So, this is level shifted here. The duty ratio of what do you mean by duty ratio of R phase? We mean, the fraction of the time for which the R phase top device is on, to the total sub cycle duration. So, if the top device is on, let us call it as t plus for a duration t plus. The bottom device is on for duration t minus, in one sub cycle. Then you can say this is t plus divided by T s. So, this is for R phase. Similarly, in Y phase you will have the top device on for some duration, and the bottom device will be on for the remaining duration. This is the duration for which the top devices on divided by the sub cycle duration; and if the task to be between 0 and 1. So, you can see that it is 0.5 plus m Y star by 2 V P. And similarly, the duty ratio here is 0.5 plus m B star by 2 V p. So, these are the modulating signals and duty ratios.

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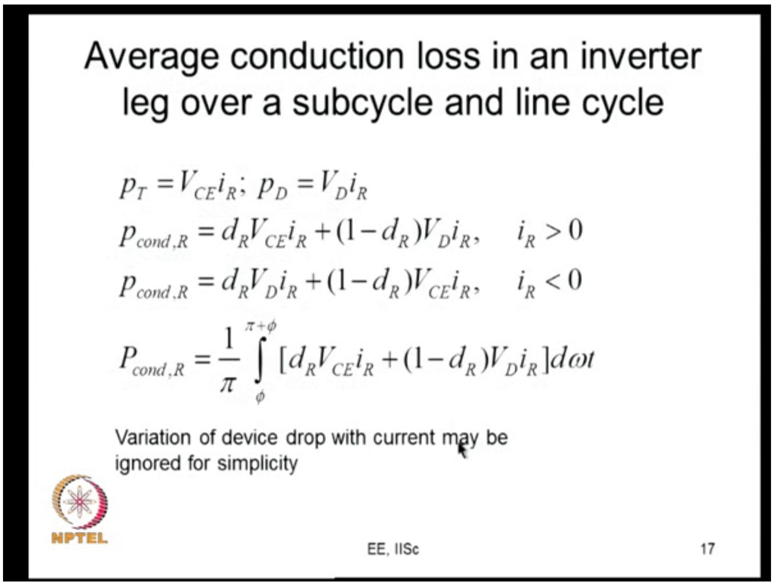

And you need these duty ratios for calculating the conduction losses you just going to see now.

So let us see; what is that conduction loss. This comes because of this drop if the transistor is conducting. If let us say a transistor in R phase like this conducting, maybe the top maybe the bottom. So, if it is conducting it has a drop of V c across z ideally, they should be 0, but practical device has something. So, this V CE can actually vary with i R, but we are ignoring that here. We are saying that we are considering an IGBT where I mean we are ignoring that variation here; we are considering it to be constant ignoring what ignoring the variation in V CE with respect to i R. So, it is like saying that the on-state devices during the on state the devices modelled more by voltage source. So, this is like V CE into i R, this is the instantaneous power dissipated in the transistor. Let us say a transistor is not conducting, rather a diode is conducting. So, the diodes conducts what current the same current i R. That is the R phase current. And what is the drop up of (Refer Time: 29:51) V D.

So, it is V D multiplied by i R is the drop cross is the power dissipated in the diode P D equals V D i R, right. Then what is your conduction loss? Averaged over a sub cycle these are instantaneously it is different. So, this is V c i R, but the translator is not going to conduct forever. Not throughout the sub cycle. How long does it conduct? It conducts only for duty ratio. So, it is D R. So, D R multiplied by V CE i R is the average power dissipated in the transistor on account of power drop.

Similarly, let us say the bottom diode is conducting for the remaining duration 1 minus D R times T s. So, what is happening is. So, how much is the average power dissipated in the diode 1 minus D R times V D into i R. This is the situation when the current is passed out. When the top transistor is conducting, and the bottom diode is conducting. And the other hand when the current is negative, the bottom transistor and the top diode will conduct. So, you will have a difference in this, duty ratio and 1 minus D R. So, you can actually write down the average loss over a sub cycle, you know either for considering the positive or the negative. In most PWM cases you do a symmetric operation.

So, it is it is enough if you probably consider only one half. You do not have to consider the 2 both the half cycles of the current; you can just consider one half cycle of the current. And you can see that this loss is varying from one sub cycle to another sub cycle. Why? Even if we ignore this variation in V CE, V CE may be 3 volts for some 50 amperes current. It may raise to 4 volts for some 100-ampere current. Let us ignore all that. Even if we have ignored all that, V CE and you have ignored this variation in V DE with current, you see that your duty ratio changes. If you have some duty ratio in this like if your duty ratio is 0.6 in this sub cycle, it is going to be something like 0.62 in the next sub cycle. And something like 0.635 ever something in the sub cycle after that and so on.

So, this duty ratio changes from sub cycle to sub cycle, and this current also changes from sub cycle to sub cycle. Strictly speaking this current has both fundamental and the ripple component, but the ripple component can be neglected. We are talking about high switching frequency cases it is not very significant. So, you can take this i R to be fundamental alone. So, this i R can be represented by some i m sin omega t minus P as I showed before. So, this is the variation now. If you call this as i m the peak value as i m this is i m sin omega t, and a minus some angle 5. So, this could be 45 degrees.

So, you have i R varying, and you also have the duty ratio varying with omega t. So, from sub cycle to sub cycle these terms vary. And they vary like this over a half cycle. And the variation in one half cycle and the variation in the second half cycle are supposed to be identical. If because you know that depends on the if your PWM is then symmetrically. So, you should not have a problem. That is, let us say your duty ratio maximum duty ratio is something like 0.8, and minimum duty ratio is 0.2. So, if the duty ratio in a given sub cycle is D, and you know or let us say some other number a. If a is the duty ratio in the given sub cycle.

After 180 degrees what would be the duty ratio? That should be 1 minus a. So, if you do that in a symmetric fashion, if the switching fishing is done in a symmetric fashion, you know the losses are symmetric in here 2 half cycle the positive or negative half cycle. So, it is enough if you just consider let us say one half cycle say the positive half cycle here, and it is actually integrated over this. So, you take the average of this. So, this P conduction are what they given is the average conduction loss over a sub cycle, and that is integrated over a half a cycle or full cycle, to get your what is called as conduction loss.

So, as I mentioned here the variation of device drop maybe ignored for simplicity. We can take the typical power drop in the IGBT. And that would give a reasonable measure of what is conduction loss, but we want a safe measure; that is when you are designing you want to know the worse case loss. You want to be sure that the loss is not going to be more than so much. So, you could normally go by the maximum V CE you then look at the maximum drop and by that you can calculate, that will give you what is called as the pessimistic figure. That is, you will get a higher your estimate could be on the higher side, but it is pessimistic. You can say that I you know my conduction loss is not going to be worst than so much. So, you can use the typical value or you can use the maximum value to get actually a pessimistic estimate of doing this now.

So, you know you can also look at this V CE in terms of i R. If you say that you need a more precise calculation. What you can do is V CE i R is available. That is available from the data sheet in some from or the other. So, this can be represented as a function of i R. So, which can be curve fitting can be done for example, if curves available. So, then you can use that and you can still do the calculations and what could give you more precise, but for simplicity is have ignored the variation. When you ignore the variation, what happens is V CE and V DE come out of this. And then this is duty ratio. So, this duty ratio, you can see that it is a function of your modulation index and omega t. And this current is a function of it is a peak amplitude, some what we can call as capital i m. And again, fundamental angle and power factor angle.

So, these are the 2 things that you have here. So, you integrate it and take the average. You are going to get the whole thing as a function of modulation index. The peak value of current and the power factor angle of current. So, with this simplifying assumption when you take V CE and V D to be constant it is possible for you to evaluate, the conduction loss in one leg pertaining to any PWM method. And you can get an expression for that. The expression will be in terms of the modulation index, will be in terms of the peak current load current and will be in terms of the power factor angle. So, it is possible to get this (Refer Time: 36:04) here now.

How does one PWM to another PWM vary this it is obvious from here. So, you may have to you may have one inverter which may be operating with PWM method one. The dc voltage is fixed the modulation voltages is same, and the ac voltage is same and the ac side current power factor are all same. But what is different? The PWM method is different. Because the PWM methods are different, the line you know harmonic currents are going to be different. Let us ignore the harmonic current. That is not significantly affecting the conduction loss, but what changes significantly is the duty ratio variation changes.

Sometimes, this duty ratio may be a sinusoid, above 0.5 which may be a sinusoid plus 0.5 in sin triangle PWM. In case of other BWM methods that will be 0.5 plus, sinusoid plus some triple m frequency component added to that. So, this D R changes from PWM method to BWM method as a function of omega t. And like what I have said before here. It is 0.5 m R star by 2 V P, and this m R star is different from PWM method to PWM method.

So, since that m R star varies from PWM method to BWM method. Your D R varies from PWM method to BWM method and therefore, the conduction loss will vary. But how much will it vary it is always the transistor or the diode is conducting. So, the variation is not much. It is only to the extent of where you know the power drop between the 2 mean. For example, if let us say the transistor has a power drop of 3 volts and diode also has a forward drop of 3 volt it does not matter at all not very significantly. So, still so the conduction loss would vary over some band, but the switching loss will vary much more significantly with PWM methods as we will see in the next lecture or we will get a feel for it even by the end of today's lecture, alright.

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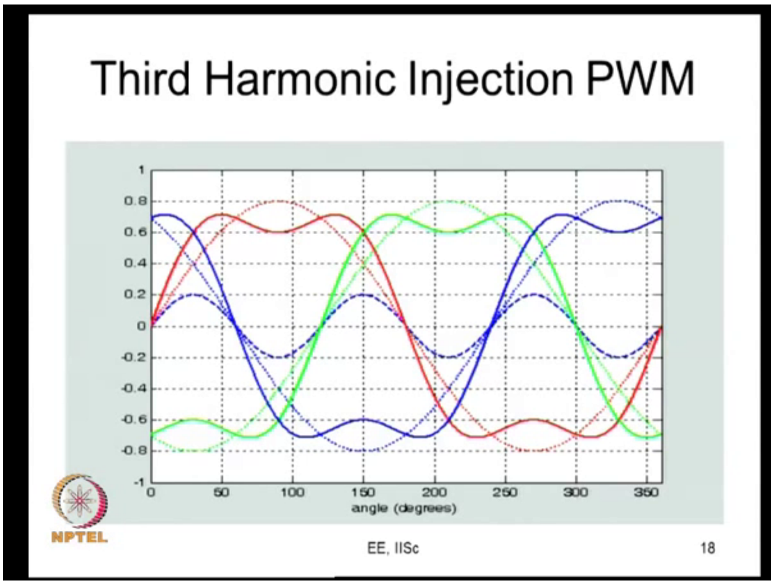

So now you go with PWM method. By PWM method I said that this procedure is common for anything now. So, it is not just sin triangle PWM, what I have done is on this modulating signal I have added common mode for all the three-phase modulating signals. So, your R phase signal looks like this. So, the common mode signal is a third harmonic signal. So, that is why I call this is third harmonic injection PWM we have seen this before.

Now, what should I do? The duty ratio I must calculate based on that. What happens in the duty ratio? It is the same nature of curve here 0 becomes 0.5. That is essentially the difference. And this is 0 0.5 and 1. You just change the scale and draw, and now this m R star will give you the duty ratio. So, you can calculate the duty ratio. Once you calculate the duty ratio, it is possible for you to calculate the conduction losses. Once again as I said before you can calculate the conduction losses the function of modulation index and you know your current amplitude and power factor angle.

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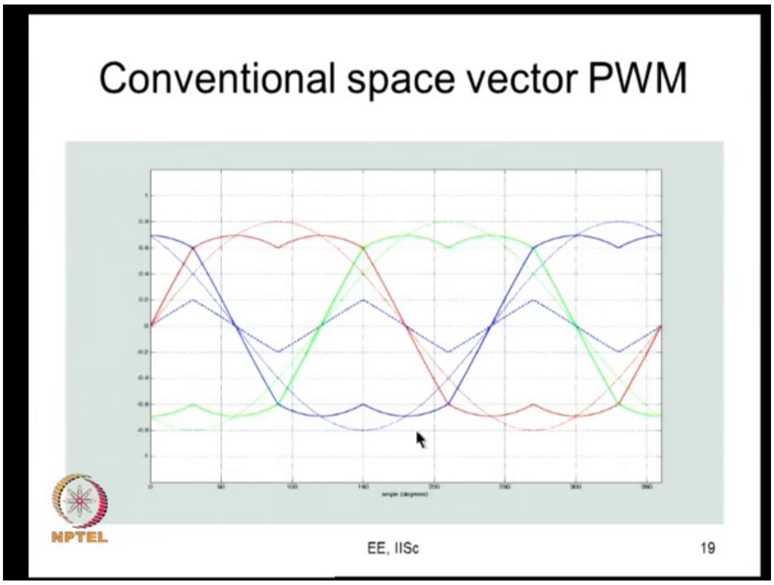

So, this is conventional space vector PWM. If the here in third harmonic injection you are with sin triangle PWM and all that the 0-vector time is there. You know, the you apply both the 0 states. And it may not be for equal duration. In conventional space vector PWM you are adding this kind of a common mode. It is not sinusoid it is not a third frequency sinusoid, but it is what looks like a triangular carrier, but it is not triangle it is actually half of the sinusoid this is half of this sinusoid and this is half of the sinusoid. This is half of the sinusoid. And what you what goes here is half of the sinusoid. So, you take the middle value of the 3 sinusoids. And take 50 percent of that, and add that as common mode and that gives you conventional space vector PWM as we have seen before. The result and modulating signal is like here. And your V m can go up to 1.15 times V P. As I as we have already discussed.

So, how does the duty ratio vary? The duty ratio variation is given by this modulating signal. So, with this duty ratio variation, it is possible for you to calculate a conduction loss.

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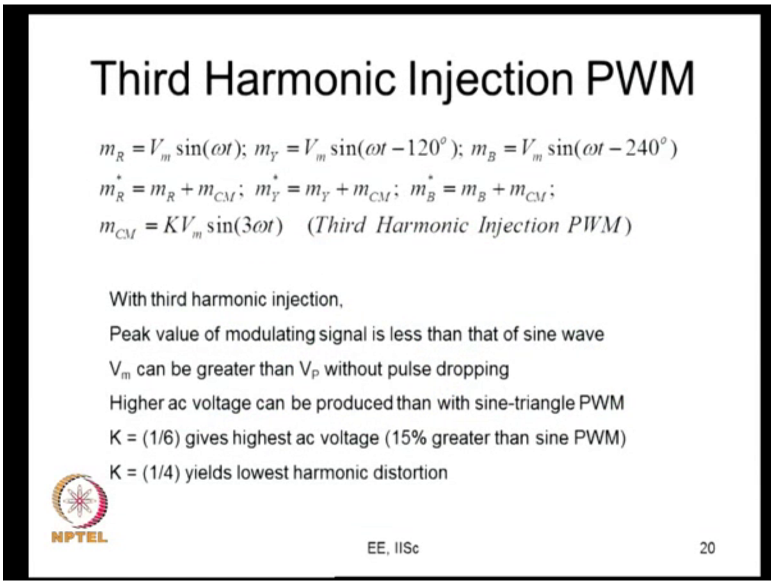

Now, let us move on. This is generically for the third harmonic injection PWM. So, as I mentioned it can be anything you know m CM, and third harmonic some k times V m sin 3 omega t where k is a fraction. Like k can be 5 percent or 10 percent or 15 percent or 20 percent or 25 percent, or some small number like that

So, what you can do is with third harmonic injection what we have seen before is the peak value of the modulating signal is lower than that of the sin. Therefore, V m can be greater than V P without pulse dropping higher ac voltage can be produced than what you can produce with sin triangle PWM and this is what we mean by dc bus utilisation. So, k equals 1 by 6, if you take this k to be 1 by 6, that is the amplitude of the third harmonic is one 6th that of the fundamental. You get the highest possible ac voltage it is 15 percent higher, greater than sin triangle. And k equals 1 by 4 yields in the lowest harmonic distortion.

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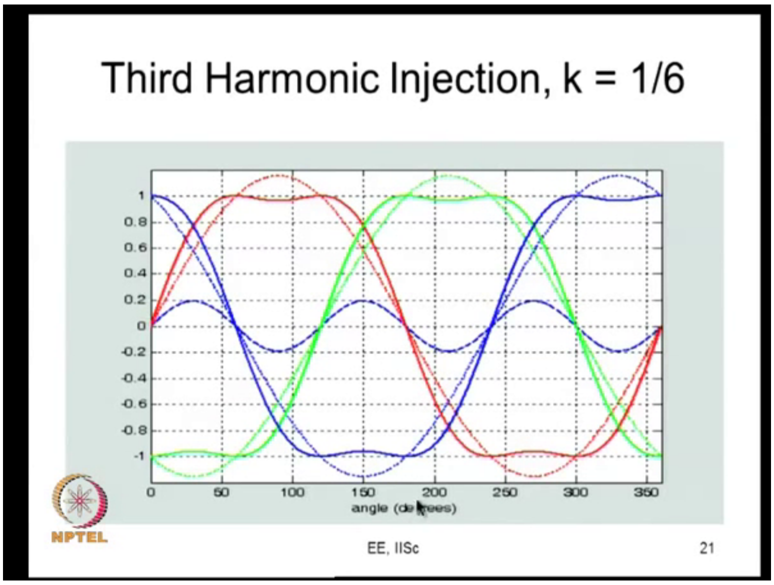

So, this is the 1 by 6 which has been illustrated here. Actually, it is about 2 by root 3 is your sign peak is 2 by root 3 times V peak, and with the common mode added you can see that your modified common mode m R star just touches 1, it does not go beyond 1. So, you are within linear modulation, and you are able to produce this PWM highest dc visualisation.

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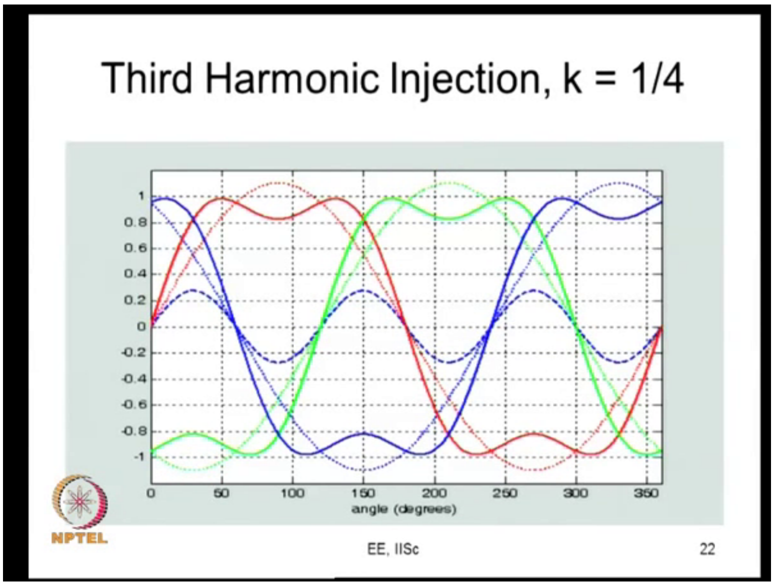

With third harmonic injection, your common mode I mean or the total harmonic distortion is minimum wave form quality is best when you add k equals 1 by 4. That is the third harmonic amplitude is one 4th of the fundamental; which is kind of illustrated here now. So, for these methods all these methods you can go by calculating the duty ratio from these modulating signals, and you can calculate your conduction loss.

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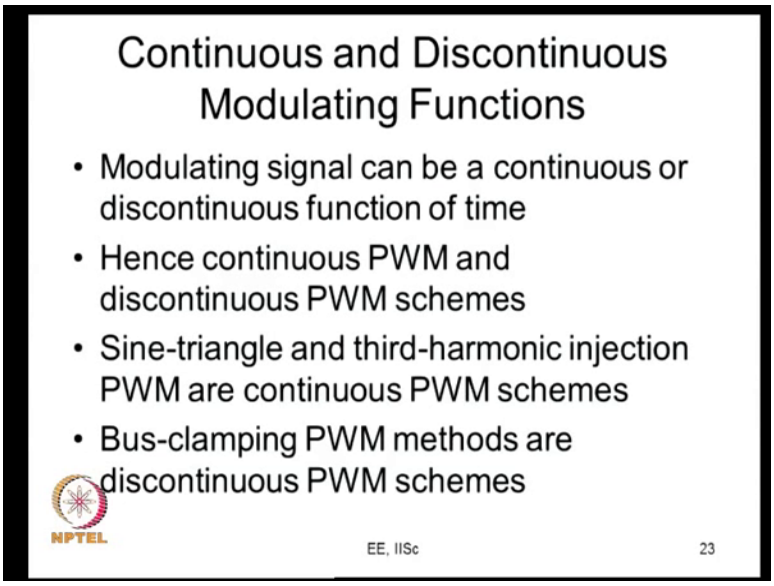

So, this is we have seen continuous modulating signals. Similarly, you can have discontinuous modulating signals. There could be discontinuous functions of time and which we call them as continuous and discontinuous PWM schemes what are examples for continuous PWM? Sin triangle, third harmonic injection, conventional space vector, PWM these are all examples of continuous PWM. What are examples for discontinuous PWM? The different kinds of bus clamping PWM methods; which we will anyway quickly again look at now.

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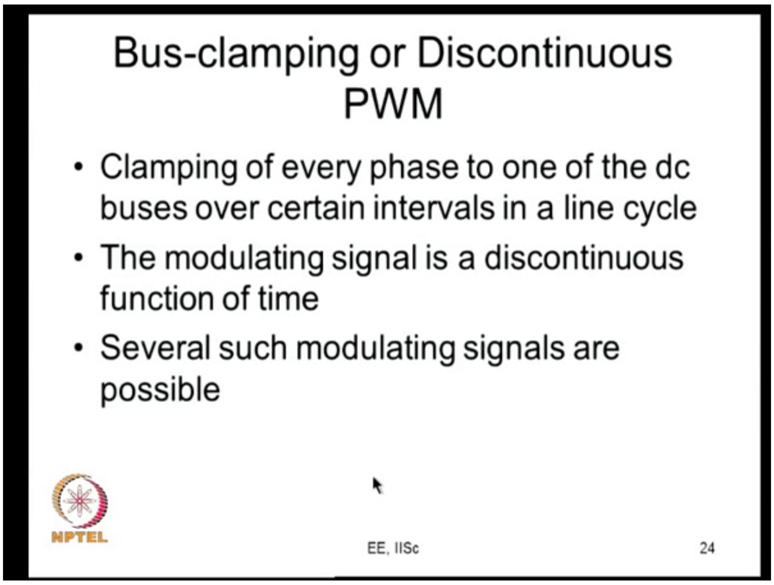

So now in bus clamping what happens? Every phase is clamped to one of the dc buses over certain intervals in a line cycle. And that is typically the phases clamped to the positive dc bus for 60 degrees and to the negative dc in another 60 degrees. So, the modulating signal is a discontinuous function of time. Then you have several such modulating signals are possible, that is what we have seen before.

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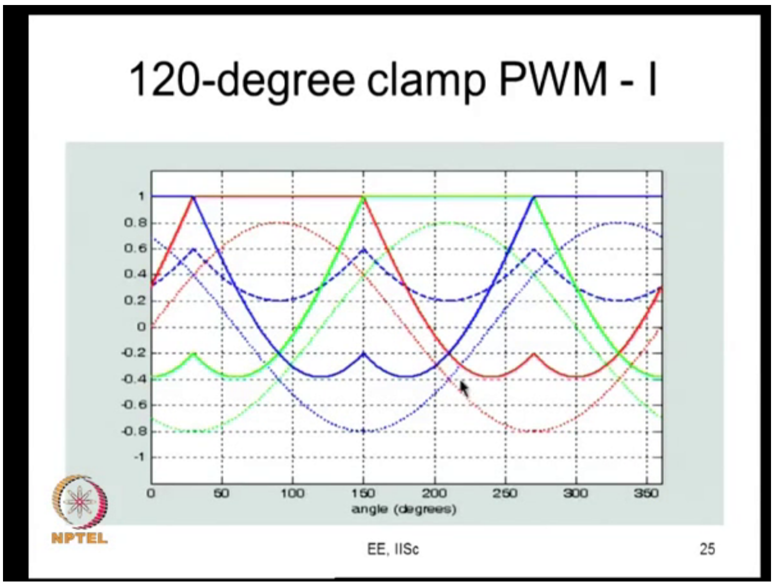

And now we are going to relook at one and see; what is the problem with the so called 120-degree clamp PMW.

What is being done? There is a 3-phase modulating signal, now you are adding a common mode. And the common mode added is like this. So, a common mode is always positive. So, what happens this goes and hits the limit at plus 1 during it is for 120 degrees continuously, and the modified modulating signal comes like this. So, what is the effect? You can see that the duty ratio is one here. But the duty ratio never goes to 0. So, here the top device is continuously on, whichever one might be conducting let us say the top transistor.

Let us say the current is unipolar the current direction is such that it is a top transfer should conduct, what happens? The conduction loss in the top transistor is going to be very high. And the conduction loss in the bottom transistor is not going to be that high. Because the first half and the second half of the modulating signals are not really symmetric, you know you the loss in some sub cycle here and the loss in some sub cycle here are not going to be equal. And the loss in the top device and bottom device are going to be unequal, and that is a problem with this 120-degree clamp PWM.

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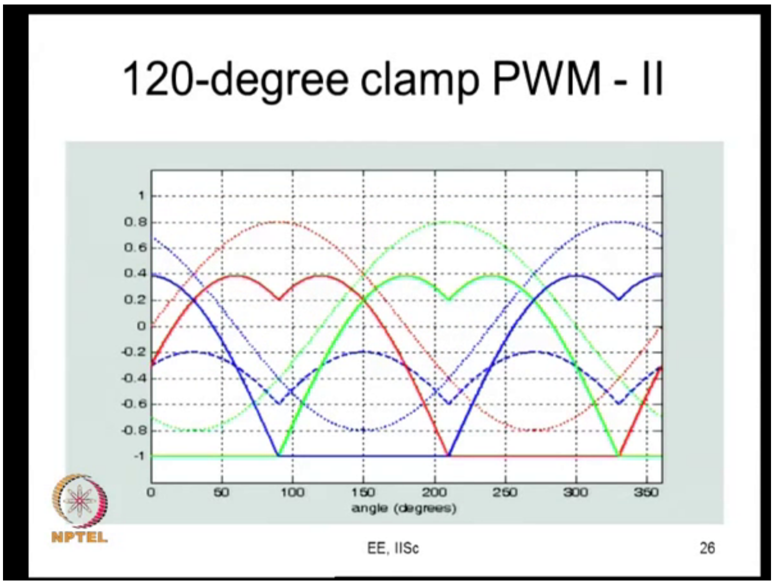

This is the other 120-degree clamp PWM here. What is happened is; you have added this kind of common mode component which is always negative. So, here the bottom device is tend to conduct for longer than the top devices. So, you can see that the bottom duty ratio is always 1. So, you may have more conduction loss in the bottom device than the top device. So, it is unequal.

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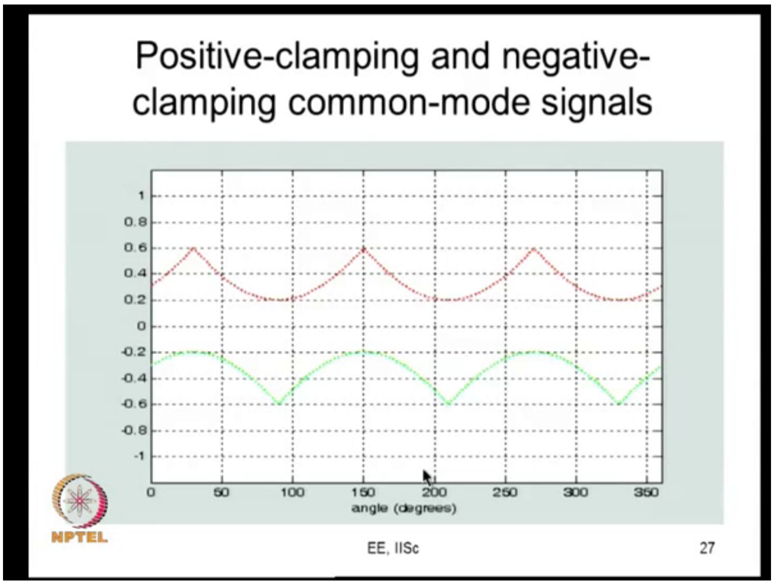

So, when you are adding this common mode, we have to make sure that the top and the bottom devices are balanced, and the losses in all the 3 are balanced. So, if you want to make sure that top and bottom are balanced, what we have is; this is the positive clamping common mode signal. And this is the negative possible common mode signal. You can either follow this or follow that.

If you follow only one, you will lead to one 120-degree clamp and you lead to this, this also leads to another 120-degree clamp, both are bad. You need to follow this for 60 degree, follow this for another 60 degree follow this for 60 another 60 this is for 60 other 60. So, that is what you need to do to get a balanced loading of all of the devices. Now which 60 that is a question. It can be 0 to 60 here and 60 to 120 here 120 to 180 here and 180 to 240 here.

That is one possibility. That gives you one PWM method or it can be let us say 20 degree to 80 degree here and 80 to 140 here 140 to 200 that gives you another PWM method. So, it all depends on which 60 you choose and which 60 you choose here now.

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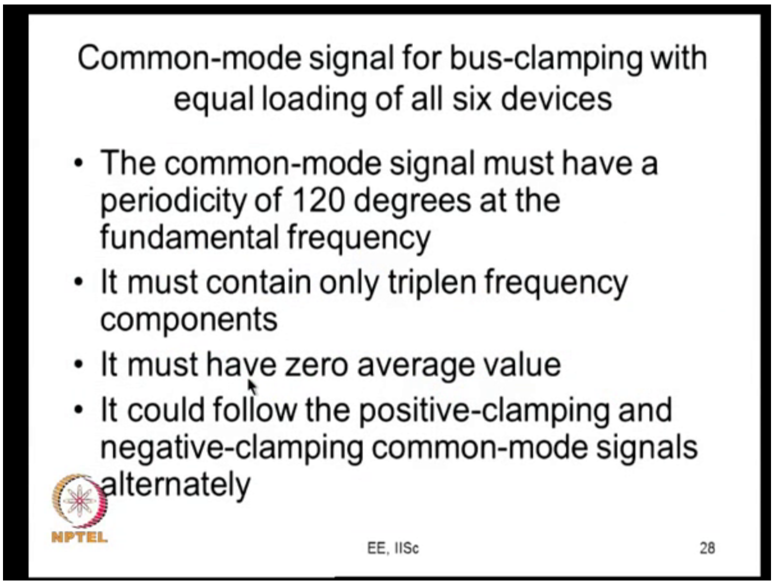

So, one simple exam; so if those are many variations, what we try to do is the common mode signal should have periodicity of 120 degrees; it must contain only triplen frequency components. So, it will follow the positive common mode for 60 degree, and the negative common mode for 60 degree. And it will also have a 0-average value.

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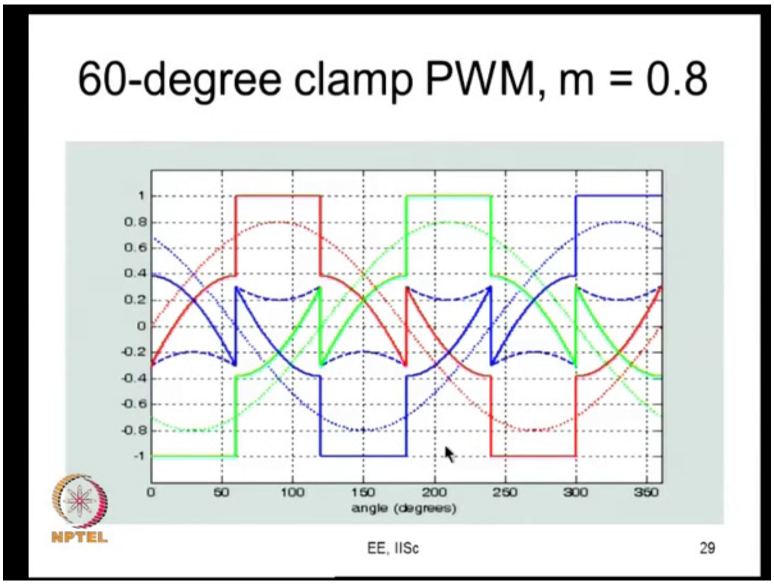

So, if you this is what we would do to come up with most of the popular bus clamping PWM method. This is one popular bus climbing PWM method, which is called 60-degree clamp.

So, this is the sinusoidal modulating signal for R phase, and the common mode added is like this and therefore, the resultant R phase modulating signal is like this. And you can see that the R phase is clamped here for 60 degrees. So, it is the top is continuously on nothing else. So, here the bottom is continuously on, here again it is clamped. So, you see that it is symmetric. Whatever is done at theta if your duty ratio is D, the duty ratio is 1 minus D here. And whatever happens to the top device is the same thing happens to the bottom device 180 degrees, later the conduction is all I mean the losses are uniform in all the devices alright.

So, this is one example of 60-degree clamp. How do you actually evaluate the conduction loss? The same procedure; now the duty ratio is given by if you have this modulating signal. And that gives you the duty ratio. The duty ratio is one here, the duty ratio is 0 here, and this is 0.5. So, if you use these duty ratios and substitute in that expression it is possible for you to calculate your conduction loss.

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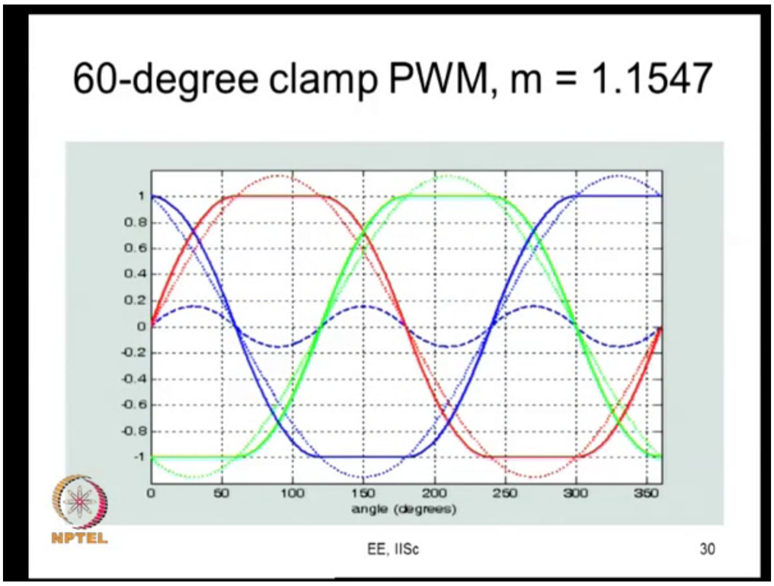

Again, this is again 60 degree clamp it is illustrated for 1 is equal to 1.1547, that is m is equal to 2 by root 3. That is the modulating signal as a peak value 2 by root 3 times the peak of the carrier. So, in this case the modified modulating signal just goes and touches one and stays at one and comes down. If you go little above this, it will go into what is called as over modulation. So, this is the highest possible thing, and again how will you do it is with the duty ratio only. The procedure is same now the duty ratio variation is as shown by this now.

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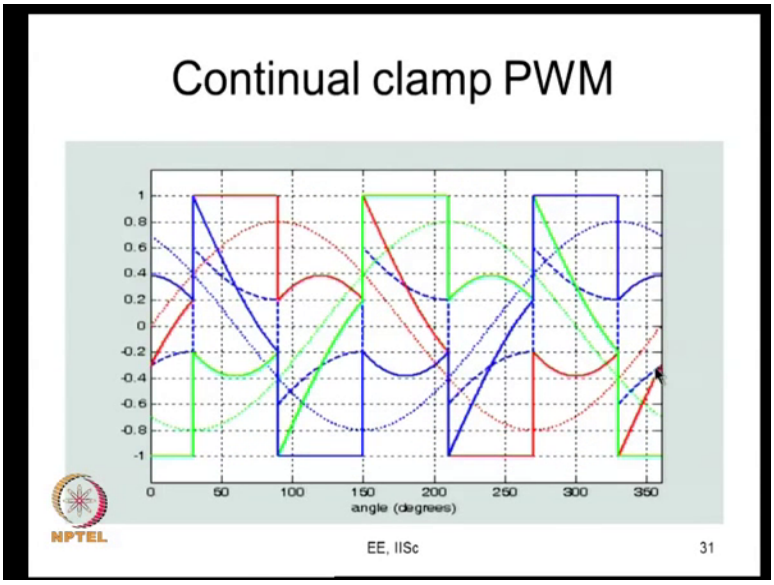

So, this is continual clamp PWM; that is 60-degree clamp is a particular case of this. This is a little more generous. So, what we have no claimed is we have not clamped between 60 to 120, but earlier we had clamped now we are clamping between 30 to 90. And again, here we are clamping it between this 210 to 270. So, this is again here is a different modulating signal, this gives you the duty ratio. You can go by this duty ratio to calculate your D R.

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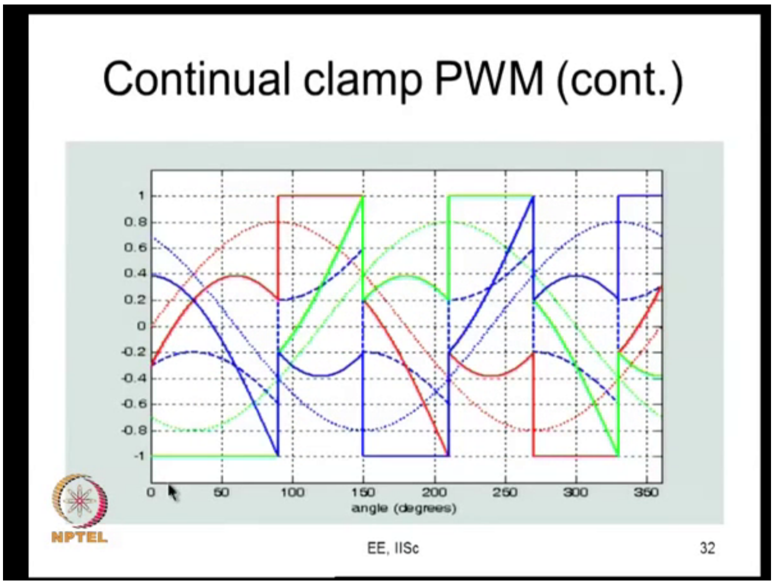

This is another clamping. So, every where once you know the modulating signal, you can find out the duty ratio. How the duty ratio varies as a function of omega t and you can do these calculations.

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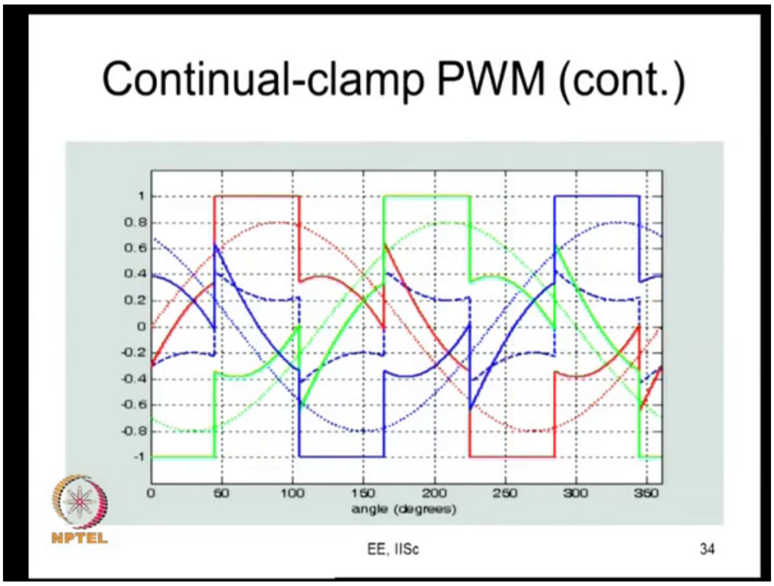

So, all various examples; so for all the continue for all the various bus clamping PWM methods you can just do this exercise.

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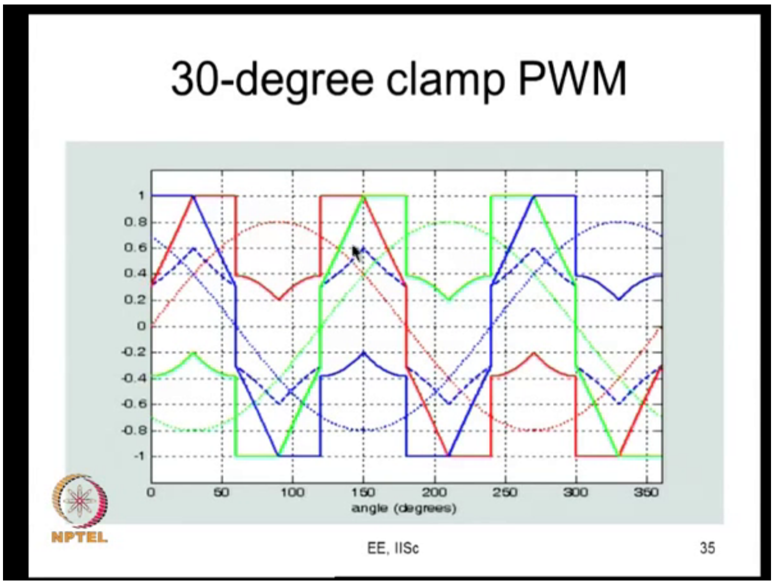

So, this is a split clamp PWM. What happens is that; it is not clamped continuously for 60 degree; it is clamped for some 30 degree here and 30 degree here. And so, we call it 30-degree clamp PWM here. So, here again if you want to calculate the conduction loss, you can see the duty ratios go by this now, ok.

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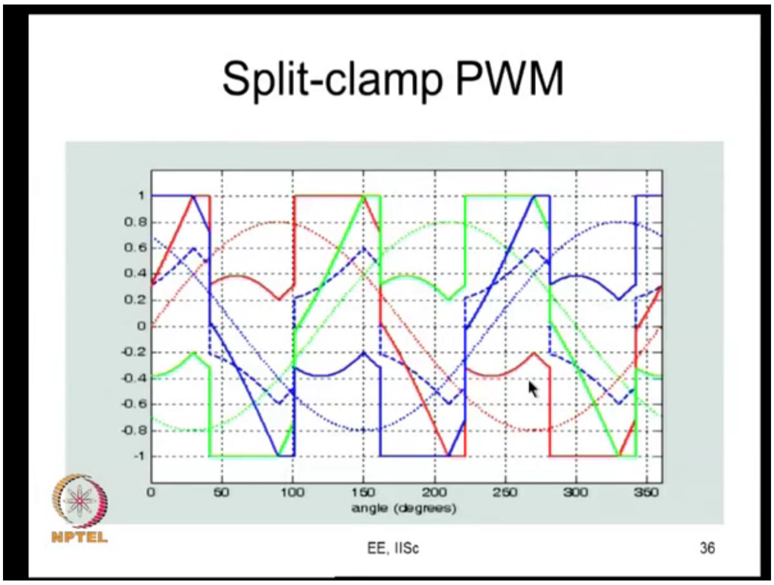

So, everywhere you can see that the same way, you know this is another split clamp. Where it is not conduction is not 30 and 30, but this is something and this is something, they add to 60 degrees. So, for example, this could be 20, this could be 40. When I see that it is 50, this is 10, this is 50. So, again this is 10, this is 50. This is if the wave form looks isometric. That is actually quarter symmetric, it is not half wave symmetric. So, whatever is you have the wave form value at theta at 180 plus it will be the negative of that. So, whatever happens to the positive device here the same thing will happen to the negative device later.

So, it is all symmetric. It looks you know lacks quarter symmetry, but as I mentioned before it is not bad at all. In fact, such a split clamp PWM gives you better harmonic distortion than this nice looking 60-degree clamp PWM. Now we are anyway talking of conduction loss. So, for anything if you have the modulating signal you know this you know you have the duty ratio as a function of angle, and you can calculate the conduction loss per leg that is the bottom.

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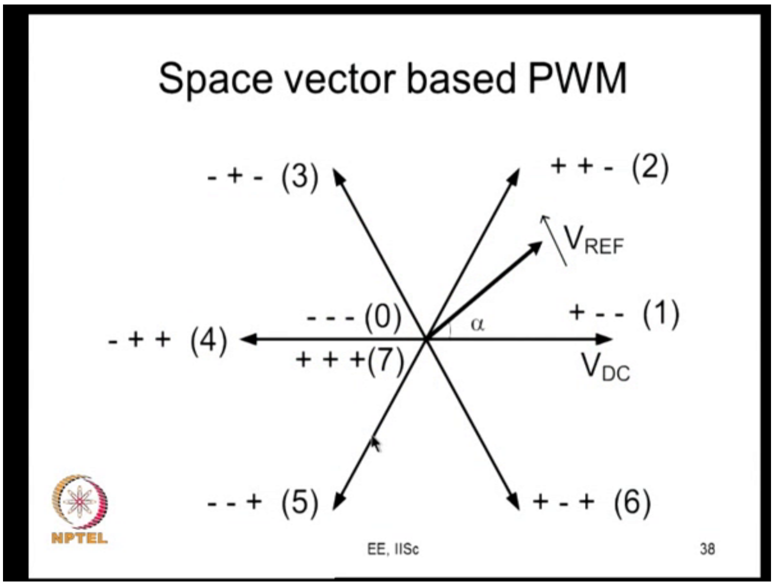

Now, if you want to do the same thing using space vector based PWM. So, of course, for continuous and discontinuous PWM methods, you can construct the method as an equivalent modulating signal and you can do that; that is always fine, but let us anyway look at it in from this point of view also. You have a revolving reference vector. You are sampling it in once and every sub cycle time.

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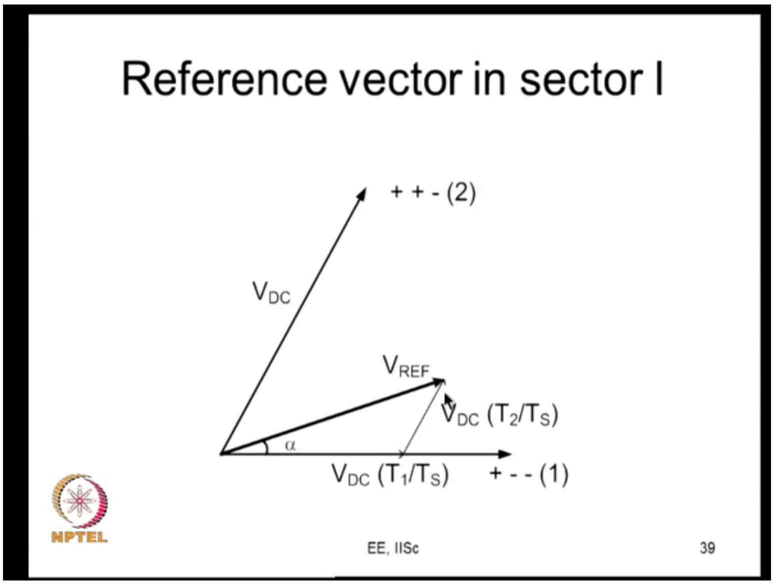

And then you are going to apply this vector for a T 1 seconds, and this for T 2 seconds, and the null vector for T z seconds. To realise this vector in an average sense, we know this.

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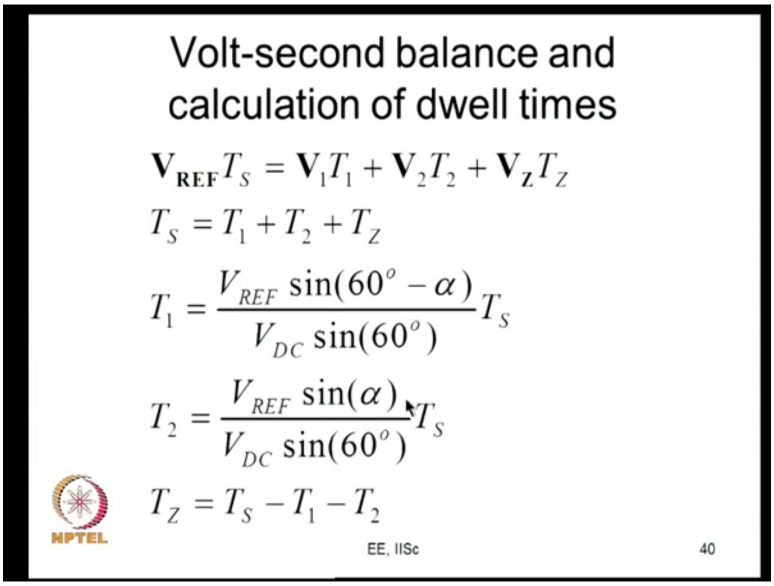

So, this is how you do your old second balance. So, V ref is applied you know V ref over T s is what you need. So, you apply V one for T 1 seconds and V 2 for T 2 and V z for T z seconds such that T 1 plus T 2 plus T z is T s. So, you have maintained your old second balance. How much is your T 1? Calculate it. How much is your T 2? How much is your T z? These are given here. So, you going do this, this is space vector based PWM.

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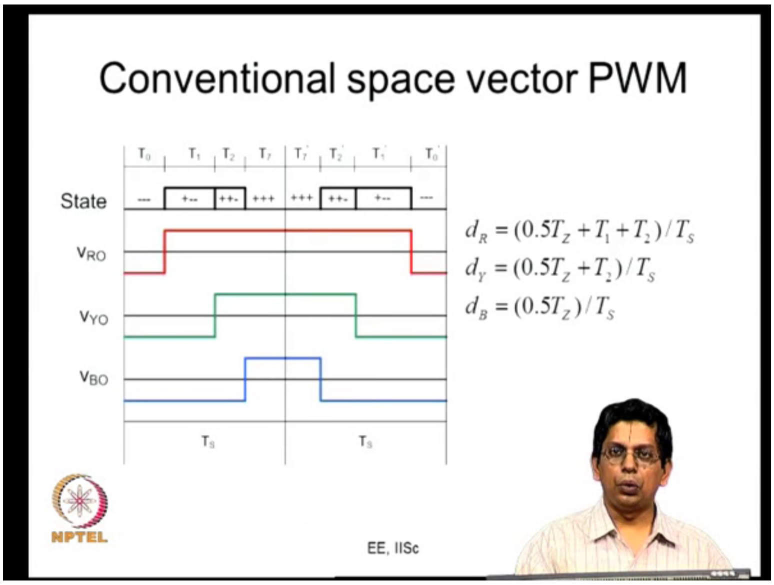

So, if you look at V ref for example, you do space vector based PWM, what happens is the inverter states are applied like this 0 1 2 7 and the R phase which is like this. Once again to calculate the conduction loss per leg, what we need it there was the duty ratio. You can actually express the duty ratio here duty ratio of R phase. That is the time for which the R phase is on divided by the total sub cycle duration. So, what is it? It is on during this 0.5 T z plus T 2 plus T 1 divided by T s. That is the duty ratio of R phase. What is the duty ratio Y phase? It is 0.5 T z plus T 2 divided by T s. What is the duty ratio of B phase? It is simply 0.5 T z by T s.

And this T 1 T 2 T z all can be calculated using a V ref and alpha. So, in case you want to do it like this, you can also express your duty ratios like this. So, you can if you can come up with your three-phase duty ratios over a sector. It is same as you know arriving at the duty ratio of every phase over an entire cycle, because the sequences are going to be used symmetrically in the 6 sectors. So, if you were want to look at it from the space vector point of view, then this is how the duty ratios can be evaluated.

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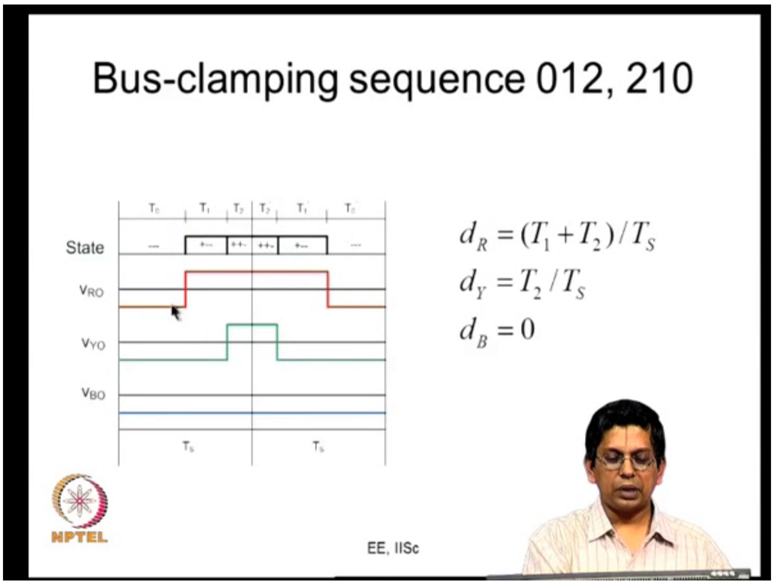

Again, if you looking at the switching sequence from the space vector point of view like this; this is bus clamping sequence 0 1 2 2 1 0 you are using only the 0 state 0. What is the R phase duty ratio? The R phase duty ratio is T 1 plus T 2 by T s. What is the Y phase duty ratio simply T 2 by T s. What is a B phase duty ratio? 0 B phase it is always it is minus B dc by 2 it does not switch at all the top device is never on. So, it is 0.

Similarly, if you look at the sequence 1 2 7 as 7 2 1 the top R phase is always on the R phase top device is always on. So, that duty ratio is 1, and D Y is given by this duration. T 2 plus T 7 by T s, and D B is given by T 7 by T s. So, you know if you are conventional or any bus clamping methods, you can also look at them like this and an evaluated duty ratio and you can go by doing it.

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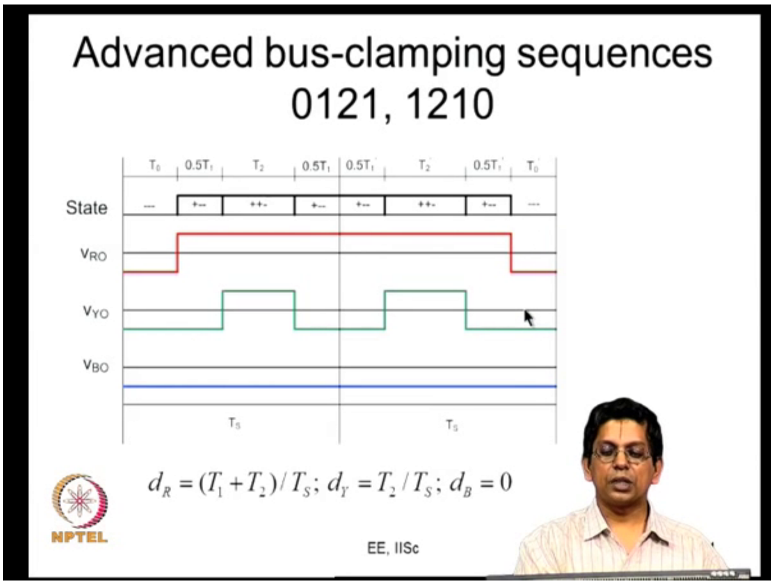

Now, if it is advance bus clamping PWM, once again you need the duty ratios. So, how do you get your duty ratio? If you look at your duty ratio of R phase, it is 0.5 T 1 plus T 2 plus 0.5 T 1; which is nothing but T 1 plus T 2 divided by T s. What is your Y phase duty ratio? The Y phase is switching twice, but still what is it is duty ratio. It is on the topic on for T 2 seconds out of T s. So, it is T 2 by T s. What is the duty ratio of B? it is D B is equals to 0. So, if it is 0 1 2 1 or 1 2 1 0, these are the three-phase duty ratios and these are same as what you get for 0 1 2.

These are actually same as what you get for 0 1 2. The same way you have the other advance bus clamping sequences 1 0 1 2, that is this 0.5 T 1 can be shifted ahead here. So, you can have 1 0 1 2 or 2 1 0 1, this can go there. So, for those sequences also you will find the duty ratio is same. So, though particular phase; which is twice it is the duty ratio you know this duty ratio for 0 1 2 1 or 1 0 1 2 is same as the duty ratio for 0 1 2.

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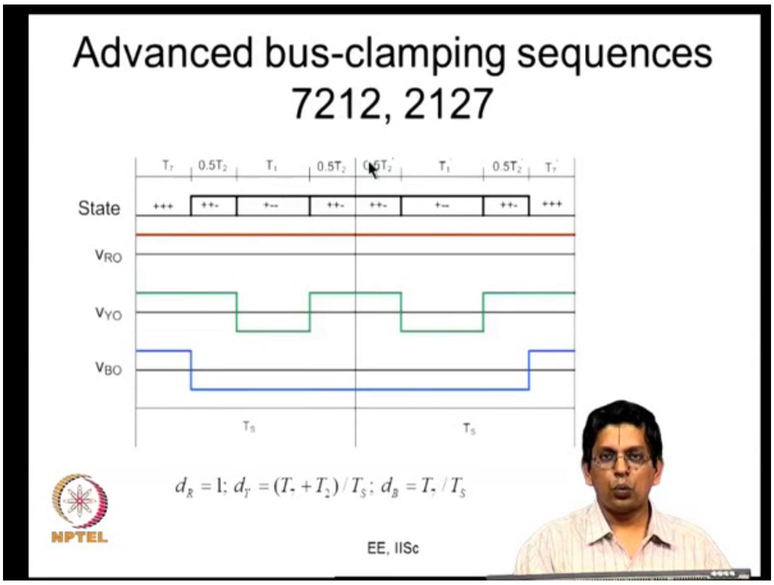

Similarly, if you look at the sequence 7 2 1 2; so here R does not switch at all duty ratio is one, what is a Y phase duty ratio? It is T 7 which is basically T z plus 0.5 T 2 plus another 0.5 T 2 divided by T s. So, it is T 7 plus T 2 by T s, what is duty ratio B phase? It is T 7 divided by T s.

So, here again this duty ratio is actually same as your duty ratio of 7 2 1, 1 2 7. The same thing can be said about 2 7 2 1 also. So, even if you have this kind of switching sequences you look at this space vector based for advanced bus clamping PWM what you can do? You can actually your calculating switching sequences based on this. I mean you can calculate a duty ratios of the different phases based on this. And you can use these duty ratios in your whole expression. If you evaluate this D R D Y D B over the entire sector 1. It is equivalent to having evaluated D RO over the entire line cycle because of symmetries right. So, you can evaluate this and you can use that in your connection loss expressions.

And it is possible for you to evaluate conduction loss for advance bus clamping PWM also. Thus, we have now looked at how exactly the conduction loss can be evaluated for sin triangle PWM third harmonic injections space vector PWM etcetera, for bus clamping PMW or discontinuous PWM. And we also seen how we can possibly do it for the advance bus clamping PMW. So, as I mentioned it is not it varies the conduction loss, varies with the PWM method, because the duty ratio varies with PWM method if you go back to that expression. You can see that the duty ratio varies, but that variation is not very high, but the switching loss you can see that it is much more significant. Because this duty ratio varies vary, but switching loss is much more let us quickly see how.

In all these know this is some continuous modulation, what happens? There is always a phase which is once, so sometimes the phase maybe carrying a high current. Let us say the power factor is near unity. So, in the modulation the fundamental voltage is high, the duty ratio is high. And you know the phase current is also high. Phase is going to switch now. Here the phase current is going to be low, but the still the phase is switching once. Here again the phase current will be high, though in a different direction the phase continues to switch. So, phase switches everywhere whereas, if you go to some bus clamping PWM method, let us say here, the phase does not switch here.

So, during this time, the switching energy lost in that phase is 0. Similarly, during this interval, the switching energy lost is 0; if so, if it so happens that the current is also having a peak here, then you are never switching the phase when the current is high. And therefore, you will save a significant amount of switching energy loss, particular when a power factor, load power factor is high. So, that is really the essence now. So, that depends on what kind of modulation signal you use, and it depends on your load power factor.

So, this is best for unity power factor load. You will be able to, you will be able to avoid switching the phase when it is carrying the highest amount of current. Again, here also it is when you are carrying highest amount of current. So, this method for example, will be very good, if your load is at a leading power factor. If you load peak current occurs exactly here it is actually very good. But if the load is lagging power factor, it may not be good. On the other hand, this is good for load with lagging power factor from the switching loss point of view. What I am trying to say is the conduction loss is influenced by PWM methods, but not simple switching loss is influenced even more by PWM method. So, you have many things. And we will discuss all this in the next class in considerable detail and when you look at here also. For example, here what happens is; you have some switching energy loss. Here you have some energy loss in both these devices if you look at the conventional sequence. You have all the 3 devices undergoing switching once and there is some energy lost here. Whereas if you look at here one does not undergo, this under goes some switching energy loss this under goes 2 losses, one on and one off.

So, if it so happens that this phase is switching lower amount of current, then and this phase is you know switching a higher amount of current, then you gain by switching this phase twice and clamping this phase. So, these are some methods we use to you know. So, we can employee the sequences depending upon you know which phase is carrying higher current or lower current or whatever and it is possible to design some PWM methods using these sequences, but to reduce your switching loss. These are certain things which we will see in the rest of this module.

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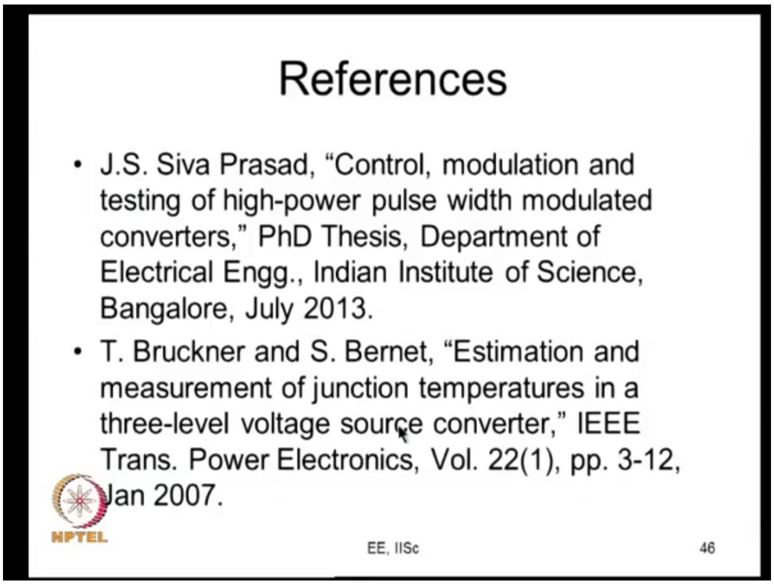

So, these are certain references which are there for your quick this thing. So, this is a PhD thesis, and this another paper.

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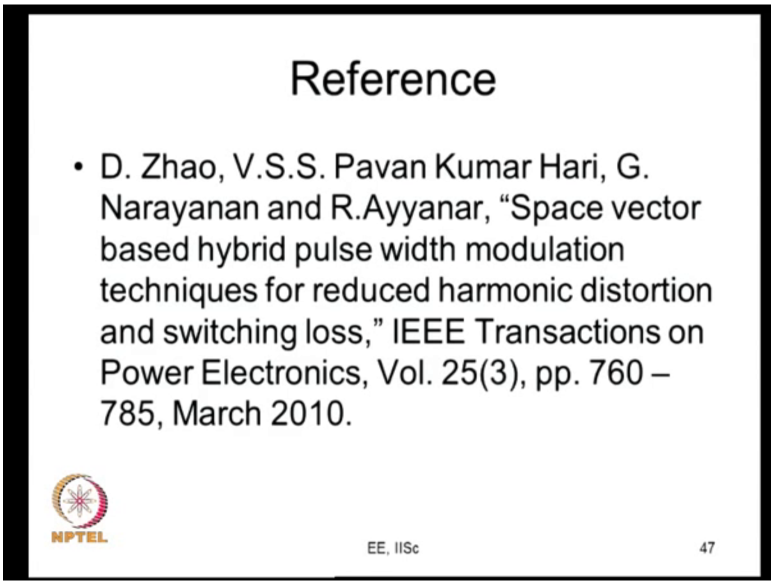

And these are this is a 8 another reference. So, this would help you something's on the losses particularly these two once loss and the junction temperature estimation. And I would discuss this give you more references in the next lecture. And thank you for your interest. And I hope you will continue to follow these lectures.

Thank you very much.