Pulsewidth Modulation for Power Electronic Converters
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Lecture - 40
PWM for three-level neutral-point-clamped inverter – III

Welcome back to this lecture series on pulse width modulation for power electronic converters. So, this is a lecture series of 40 lecture series and this is the concluding lecture. So, we had 13 different modules and the last module is been on multilevel inverters for pulse width modulation for multilevel inverters, and this is the third lecture in that module and this is the fortieth lecture in the entire series. So, I welcome you to this concluding lecture of this series of lectures now.

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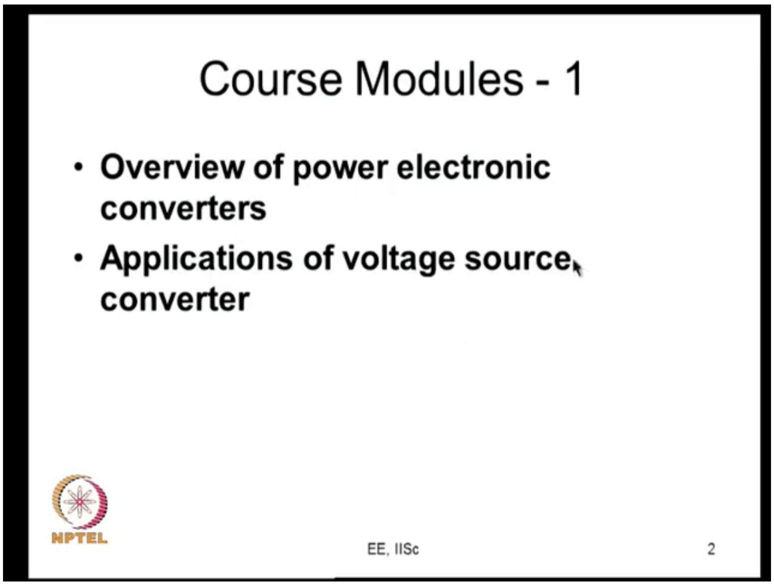

So, it would be good to take an overview of what we have been doing here. So, in the first set of modules we basically covered the different topologies, where this is where we discussed the basic neutral-point clamped inverter topology as well. And we looked at different applications in a couple of two or three lectures, we looked at what were the applications and we looked at things like motor models and how you can model the mains as seen by the inverters and so on. We looked at the fundamental and the harmonic equivalent circuits etcetera.

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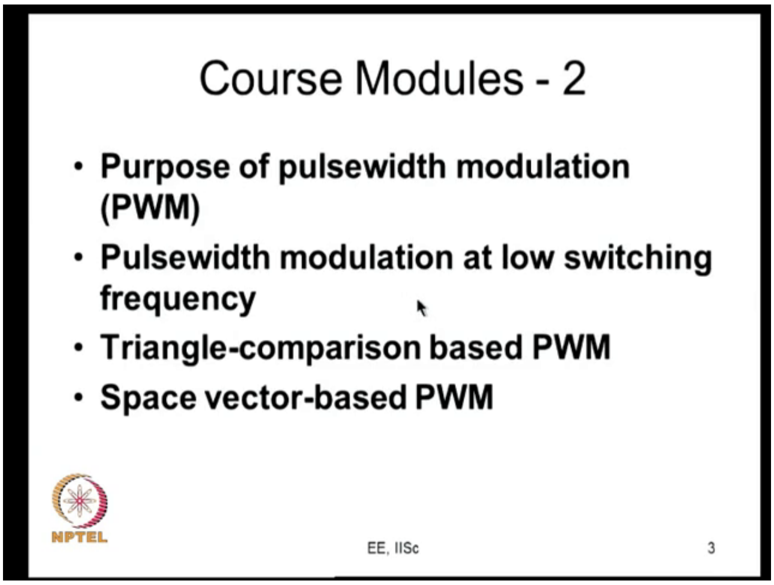

Then this module set of modules they normally they pertain to the PWM generations. So, we looked at Fourier serious and wave form symmetries so on. And then pulse width modulation at low switching frequency particularly how would you do selective harmonic elimination and we looked at such things here. And the effect of the switching angles on the harmonic voltages; the fundamental harmonic voltages try to study and will designing some low frequency PWM method. Then we looked at triangle comparison base PWM and space vector base PWM, where you are assumed switching frequency or the inverter switches at a frequency much higher than the maximum modulation frequency of the inverter. So, this set is broadly on the PWM generation.

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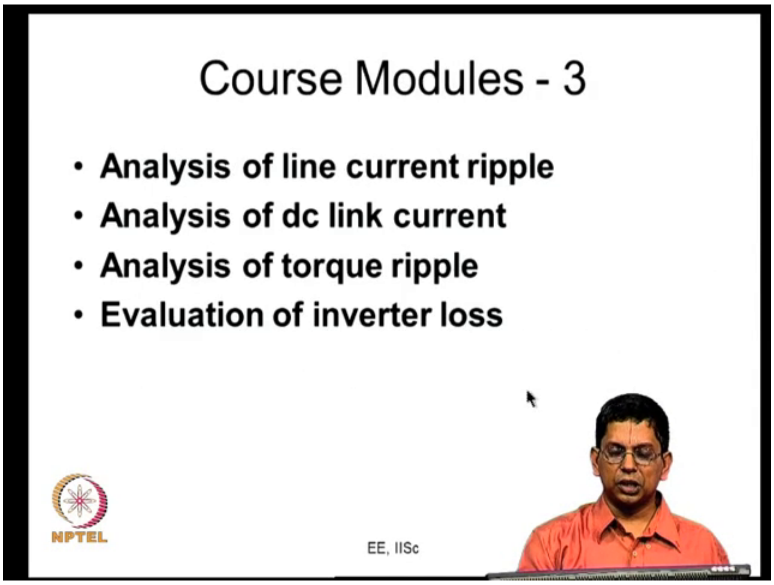

And then this is all on the analysis part, and this is all about the two-level inverter, so that is here also we considered essentially the PWM generation for two-level inverter, here also we have been looking at the analysis for two-level inverter. How do you calculate the RMS current ripple, how do you calculate the dc link current, and then some ways of estimating the ripple torque that is there whether it is when you are running an induction motor from sinusoidal voltage, there will be a only steady pulsating torque.

But you are feeding it from an inverter, this is not fundamental component alone they know there are also harmonic components and they result in harmonic fluxes and harmonic currents. The fundamental flux would interact with harmonic currents and the harmonic fluxes would interact with I mean the fundamental current would interact with harmonic fluxes and produce pulsating torque and this we did some analysis on this also and then we went about evaluating the inverter loss. So, many of the first three particularly you know these are all actually more or less directly extendable to three-level inverter also.

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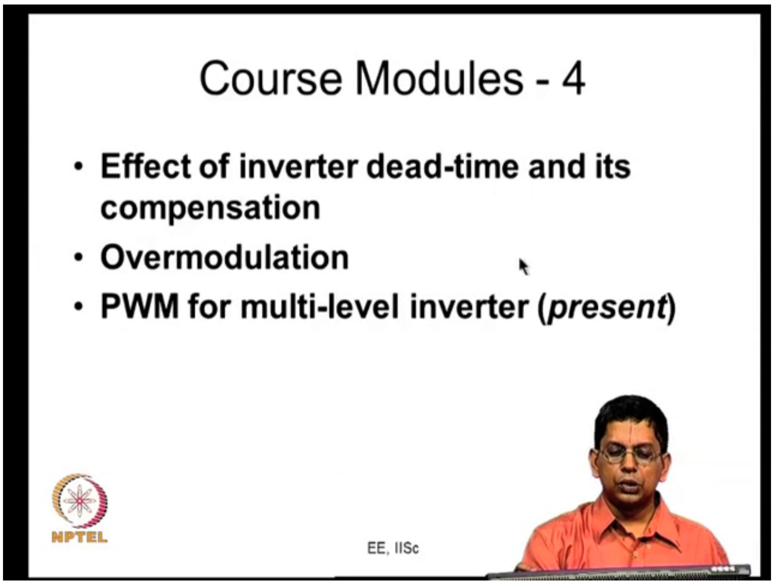

So, here there are some effects of dead-time over modulation. And now we have been into the last module on multilevel inverter.

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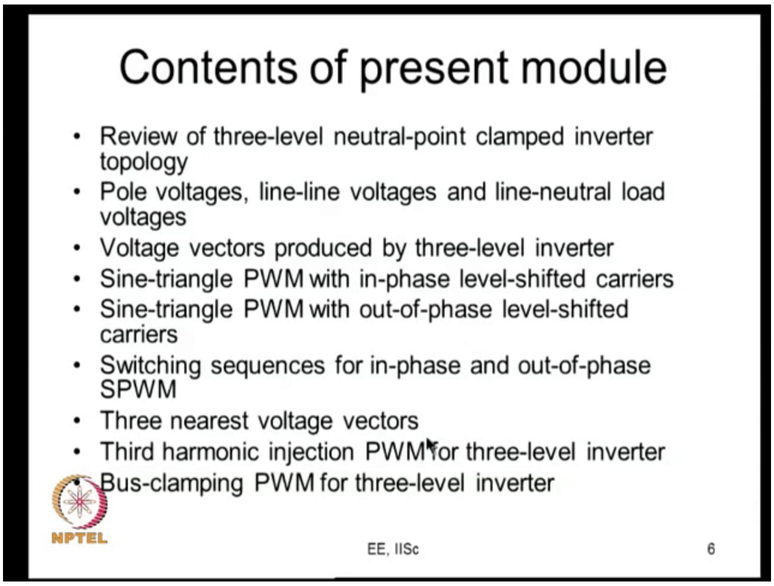

So, as I have said in the previous lecture, so these are the contents that we had in the present module. So, we initially reviewed the neutral-point clamped inverter topology and we looked at the pole voltages line voltages and line to neutral voltages how they are related here. And the essential difference here is that you know in two-level inverter the pole voltage can be only plus V dc by 2 and minus V dc by 2 and here it can be plus V dc by 2 minus V dc by 2 or 0.

So, this intermediate voltage level it leads to many more voltage levels like five different voltage levels for I mean values possible for line-to-line voltage. And again more possible instantaneous values for line to neutral voltage, and this is what is responsible for the improved waveform quality. And you know voltage vectors they are produced by the we have about 27 inverter states and two-level inverter like once understand two-level inverter and the basic concepts dealing with three-level inverters not at all a problem.

So, in two-level inverter, we had 2 raised to the power 3 - 8 inverter states here we have 3 raised to the power 3 - 27 inverter states. For each inverters states it is possible for us to look at what the pole voltages are which we did. And then correspondingly we can find out what those line-to-line voltages are, and correspondingly we can find out what those line to neutral voltages are. Once you have is line to neutral voltages, you transform them into the stationary reference frame you know alpha, beta and you get your voltage vector and these would be the voltage vectors produced by three-level inverter.

What we found was in a case of two-level inverter there are 8 inverter states, they produce six active vectors and the two 0 states produce one 0 vectors. So, eight states produce seven distinct vectors, here we found 27 states producing 19 distinct vectors. So, there is lot of redundancy. What you mean by redundancy, there are more number of inverter states producing a particular vector state I mean the voltage vector then you call it redundancy. Now, if you have vector a particular vector let us say the vector is of length pa V dc and it is angle 60 degree you know its uniquely possible its only one unique inverter state maybe possible.

Let us say another one you have 0.5 V dc angle 60 degree that is the vector, so that vector symbolises three phase voltages or you know the line-to-line voltages, so that vector it is possible to apply using two different inverter state. So, that is redundancy in the case of three-level two-level inverter we discussed the said length what is the redundancy the redundancy is in the 0 state. The 0 state you know 0 vector can be producing using two different 0 states here the same 0 vector can be produced by three different 0 states, and also there are six vectors of length 0.5 V dc, they can be each of them can be produced by two inverter states.

So, the redundancy is in a three-level inverter or much higher than what you have in two-level inverter. So, in two-level inverter you can design in. So, many PWM methods in three-level inverter you can design much more than that. So, what we are trying to look at just some idea you know how possibly you can do this you know some ideas that will get us going. And you know please bear in mind what I am talking is it is actually only the starting process I mean it is not a you know not a final thing, these are all inputs enabling inputs for you. So, that you can do further and you can do more work on pulse width modulation or you know work on PWM converters in various way.

So, we are just trying to get some introduction and basic idea on how exactly you can do that now. So, remember we had so many lectures we discussed about PWM for two-level inverter. So, if we extend that in three-level inverter offers much more possibilities than that. So, you have you know much more things are actually possible in a three-level inverter. So, we are just trying to understand the fundamental concept, so that you know we will be able to deal with you know analysis of some non PWM methods or probably come up with some new PWM method design or whatever, so that is what we have been trying to do now.

So, if everything you did like sin triangle PWM we did for single phase I mean for a two-level inverter we tried to extend it for three-level inverter. In the case of two-level inverter, it is fairly simple because sin triangle PWM there is one sinusoidal modulating signal for a phase you are going to compare it with a triangular carrier. So, its output is going to be giving you the gating signal, top and bottom device devices are complementary. Whereas, if you go for three-level inverter the same sin triangle PWM you may have one modulating signal, but you know your inverter leg your R phase leg is not having only one you know it has actually two sets of complementary devices. So, you need two gating signal.

So, one of them we saw that you know the same sin PWM then you can one possibility is you use a modulating signal, single modulating signal and compare it with two-level-shifted carrier, this is one possibility. As I mentioned to you to the other possibility also exist that is you use two modulating signals corresponding to particular phase R phase and compare it with a single triangular carrier also. There is such a PWM method also I am not discussing that PWM method here and that is covered in some of the references that I have already indicated to you.

So, now this is one way of extending to two-level-shifted carriers. So, if they are level-shifted carrier, what do you mean by that. So, your modulating signal, earlier in sine triangle PWM you know for two-level inverter, we considered the carrier, carrier to vary from minus 1 to plus 1. Now, what we do we have two carriers carrier one would vary from 0 to plus 1; other one would vary between minus 1 and 0, so this two-level-shifted carrier. And again it is not necessary that they have to be in-phase they could have some phase difference also. So, we looked at this in-phase and the out-of-phase issues now this comes because of you know such kind of thing is not there in two-level inverter you use a single carrier only.

You use such ideas for example; when you go you know when you talk of parallel inverters when you have inverters connected in parallel to the grid or running a motor. Sometimes what you do this so called carrier interleaving that is you have two inverters you know they are connected to parallel to the grid through let us say line inductors. Then what you can do is you know one will be compared with some carrier at some 5 kilo hertz, other one will also be compared with I mean the modulating signals or will be compared with the carrier at same 5 kilo hertz. But these two carrier will have a small phase shift like 90 degrees or 180 degrees at the carrier frequency, this idea that you know carrier interleaving is very interesting idea that has been used extensively in parallel converters.

Now, what we are trying to do is in the same leg only you know the same sinusoidal signal you can level-shifted carriers. There is no real advantage by doing this in many cases you can actually use out-of-phase, but as we just discussed in the last lecture in-phase level-shifted carriers are better than many other possibilities. So, like they give you low harmonic distortion. Then we looked at the switch switching sequence. So, you want to see what inverter states are getting, what you mean by switching sequence. We are looking at this state in which the different inverter states are I mean states are applied when you use a particular PWM method now.

This is actually the link between your triangle comparison base PWM and this space vector base PWM. So, there are two different approaches and you actually link them nicely doing this now. So, you consider any carrier comparison PWM method. So, what you do is look at one carrier cycle or look at one sub cycle and see what is this switching sequence like. So, that gives you an very good idea how it is going to work now.

So, you can compare it with some space vector base PWM methods more easily. And once you know that doing this analysis, you know the voltage vectors that are getting applied it is carrier comparison PWM, but you know what are the voltage vectors getting applied and in what sequence they are getting applied. So, you can calculate the error voltage vector and you can integrate and even you can do those analysis like this stator flux ripple analysis which we did earlier.

So, we ended I mean in the last lecture we had some things on the switching sequence for the in-phase and out-of-phases SPWM, this is what we looked at. And this switching sequence for third harmonic injection pretty similar to that and what we found out was that in many of this cases the when you use in-phase PWM particularly the three nears voltage vectors are the ones that are often getting used, so that is what comes up. Whereas, in the out-of-phase cases, it is not the three nearest voltage vectors that is one significant finding there. Then like in on the sinusoidal PWM, you can add third harmonic, you can also add some other common mode signals which would lead to bus-clamping.

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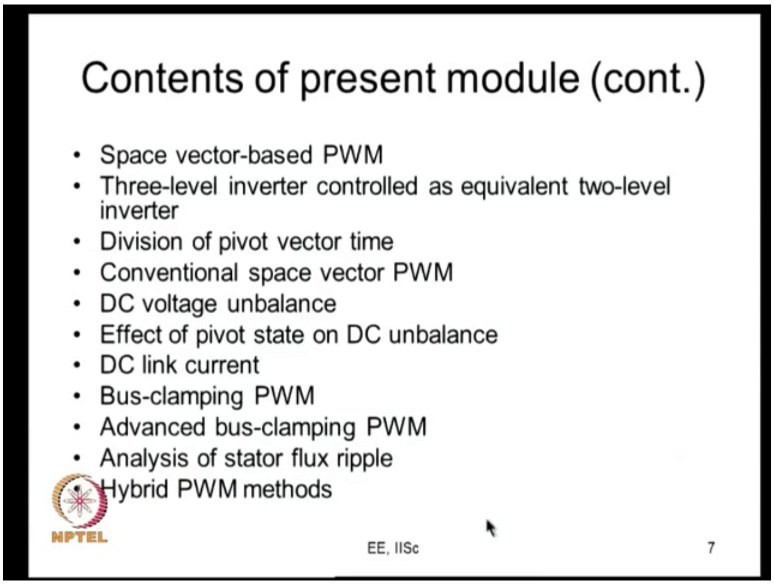

This is what we looked at towards the end of that in the last lecture. And we will be looking more in terms of space vector based PWM, three-level inverter controlled as equivalent two-level inverter and so on and so forth and more number of topics that we would look at today. So, when you do this what is essentially you are doing is this three nearest vector, what happens is what are the three vectors you know if you look at the sequence in which they get applied, you normally start from one vector whose magnitude is 0.5 V dc and you come back to the same vector. And that vector we call it as the pivot vector. This is equivalent to your 0-vector in a two-level inverter case now.

So, this pivot vector time is divided differently, just like this 0 vector time is divided differently in three-level in two-level inverter this pivot vector time is divided differently by different PWM methods in a three-level inverter. In conventional space vector PWM, you divide this pivot vector time equally between the two now. And if you really see that the you know the pivot vector time is all right, you know you can apply the pivot state one or pivot state two, you know there are two pivot states. But they have some influence on the dc voltage unbalance that is something we will take a look at now.

And you can look at so the effect of pivot state on the dc voltage unbalance. And we will also quickly see how you can work out you can evaluate the dc link current for a three-level inverter as we tried to evaluate for a two-level inverter. And we would look at bus-clamping PWM from the space vector point of view now. Because you know when you use the pivot vector divide your using two pivot states here we will be using only one pivot states. Just as in two-level inverter you use only one 0 state instead of two year, here you will use only one pivot state now.

And we will do this advanced bus-clamping PWM which we discussed for two-level inverter we will see how this can be extended to three-level inverter. And then we will go on to see the error we will look at the error voltages in the various cases and then we will try to integrate you know you can even once you understand that you can integrate and get the stator flux ripple and do an analysis very similar to what did we before. And possibly you know we will just see how you can start coming up with hybrid PWM methods here also.

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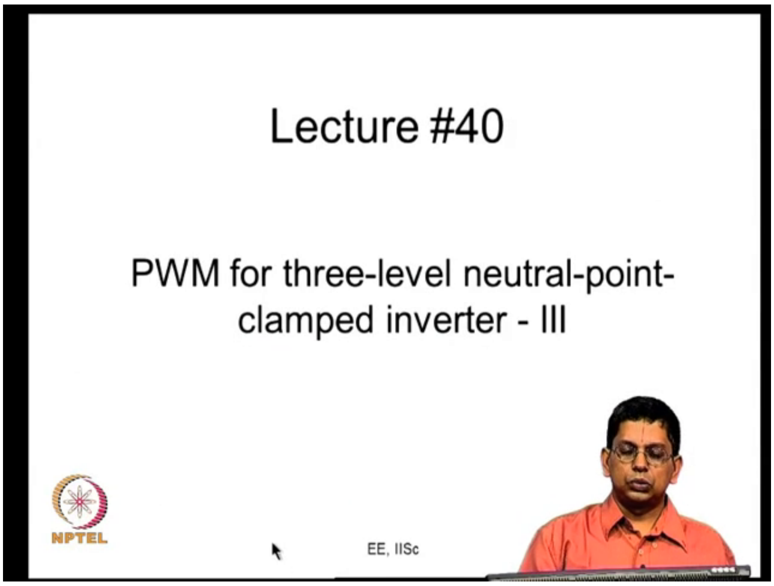

So, this is PWM for three-level neutral point clamped inverter lecture three. So, third lecture in this, last lecture in this particular module.

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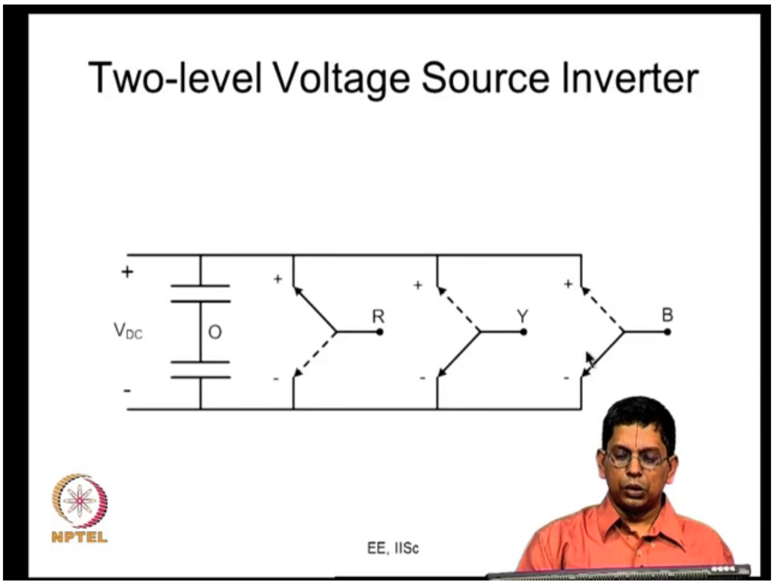

So, this is three phase voltage you know two-level voltage is inverter, each leg is a single pole double throw switch.

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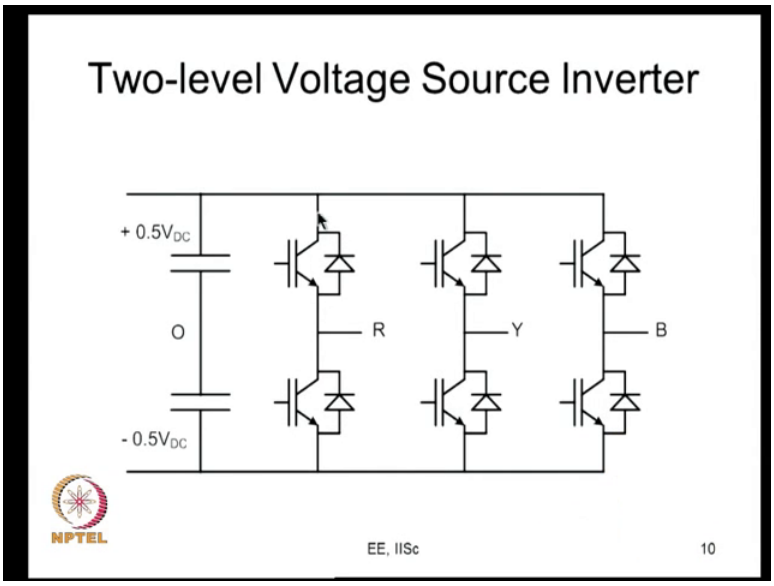

They are realised like this. These two switches they switch in a complimentary fashion and the switches can block voltage in one polarity, the collector positive with respect to ammeter and they can conduct in both directions that the transistor can conduct in one and the diode can conduct in the opposite direction.

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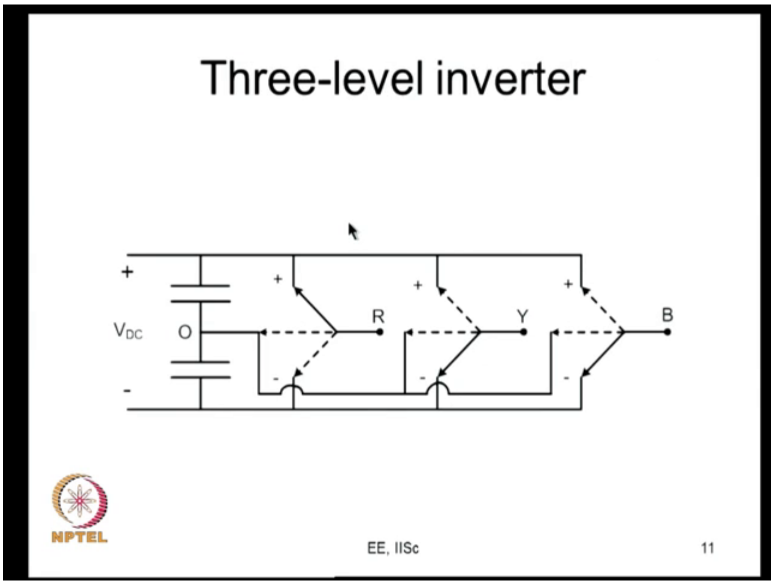

The three-level inverter in every leg instead of being a single pole double throw it is now single pole triple throw switch, the throws are connected to the positive bus negative bus and dc neutral. Here also positive negative on the dc now is it fine.

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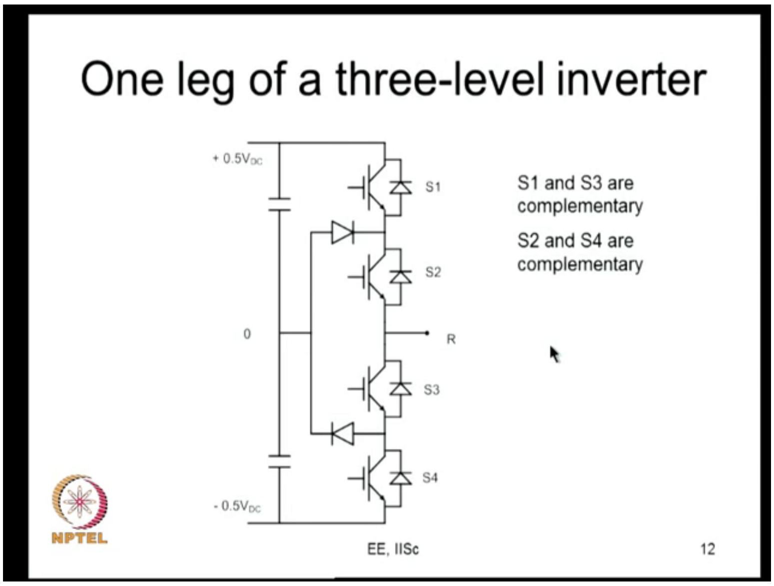

So, now you have one leg of a three-level inverter, which is been realised here. So, this is something we looked at in the first module and we also looked at I mean briefly looked at this in the subsequent I mean the past two lectures in this module. So, this S 1 and S 2 and S 3 and S 4, when both are on R is connected to the positive; when these two S 3 and

S 4 on R is connected to the negative when the middle two are on R is connected to the midpoint. So, you find that the S 1 and S 3 are complementary and S 2 and S 4 are complementary we saw this in both the previous lectures now. So, PWM required that we generate the signals for S 1 and S 2, when S 3 and S 4 can be generated as compliments of S 1 and S 2 respectively.

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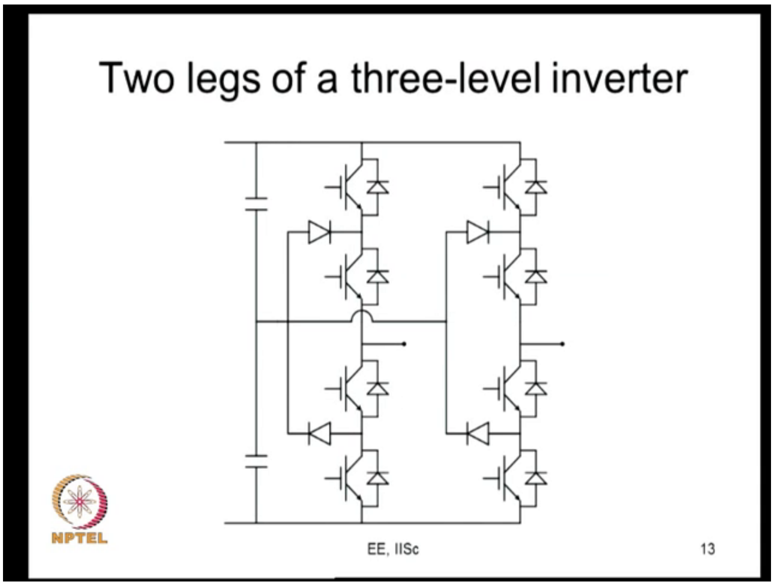

So, this is two legs of three-level inverter. And if you are using a single phase load for some reason or you know let us say there is a single phase source whose power you want to tap on separate some dc load, you could potentially do this.

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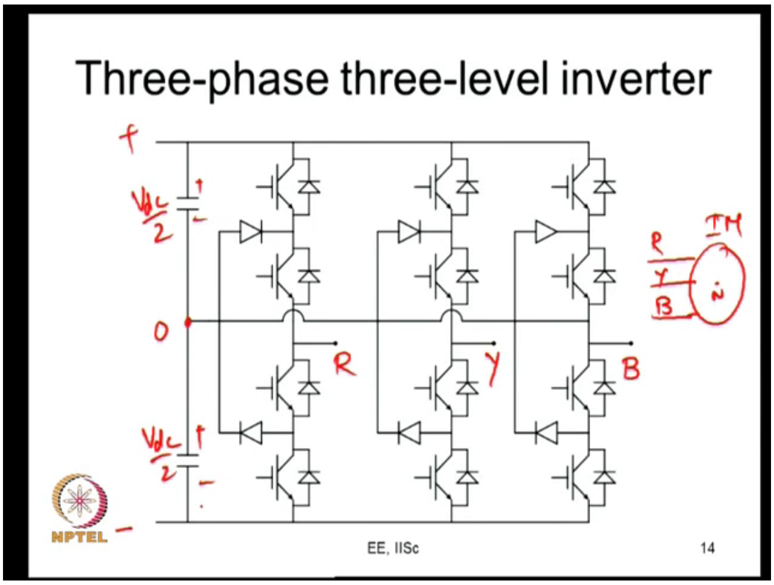

Now, this is three phase three-level inverter which we have been talking about. Remember all these space vector PWM all that are actually valid for three single cases not really for single phase. For single phase inverter also we discuss some PWM we looked at some even harmonic injection also in one of our lectures in the triangle comparison based PWM, in that module we discussed one. All the space vector PWM idea and all the third harmonic injection common mode injection are all ideas which are actually applicable to three phase. In fact, they are extendable to five phase, seven phase etcetera also.

So, this is the inverter that we are actually looking at. So, let me quickly indicate the important terminals we will have. So, these are R, Y and B terminals, these are the terminals of the load you can probably assume that an induction motor R, Y, B is connected here. And it has some midpoint neutral which is not connected anywhere. So, this is positive terminal, this is negative terminal, and this is 0 and we have V dc by 2, and you have another V dc by 2 this polarity. So, this is a three-level inverter now.

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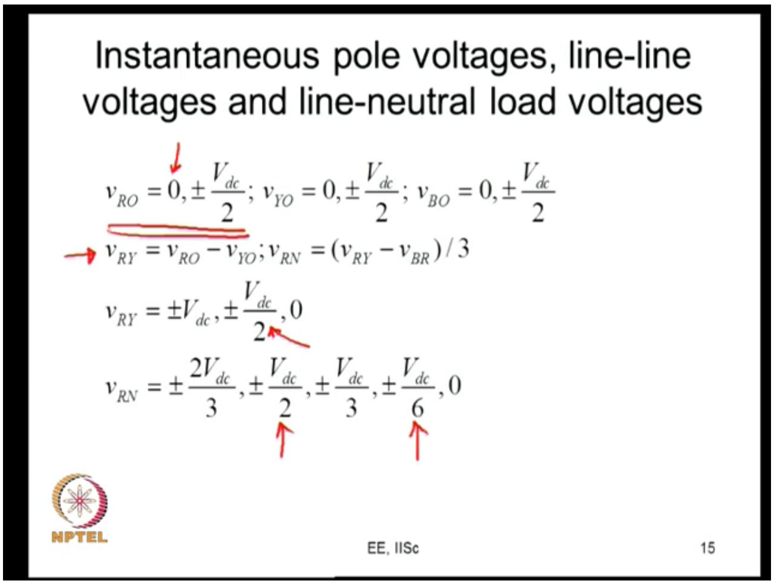

We had already seen this. So, V R o can take this value and this is 0 is what you do not have in a two-level case. And this relationships are similar to what you have in a two-level inverter. Now, again because your V R o is this additional 0 is there in V R Y you have the additional value which is not possible in two-level which is possible in three-level. Again these things are what you do not have in two-level, but you get in a three-level inverter because of this additional voltage levels being available. So, the inverter output can follow the ideal out desired output more closely and can lead to improved a form quality.

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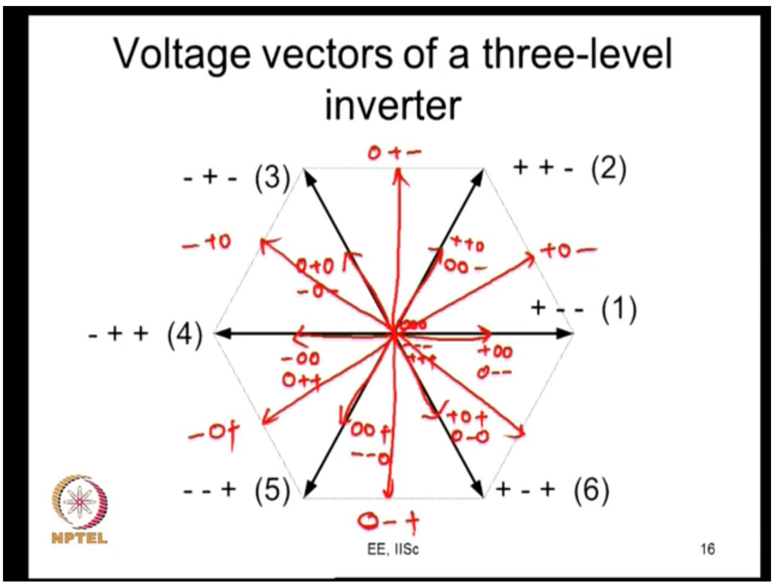

So, this is what is our voltage vectors now of you know basically it gives for two-level inverter, we can quickly fill this up to show how it is three-level inverter just as a an exercise plus minus minus. So, you have plus 0 0, it will be half of the length of the vector that you know corresponding to plus minus minus. So, plus 0 0 and 0 minus minus produce the same set of three phase line-to-line voltages. So, their output is this is like this now. Then let me consider the set plus plus 0 and 0 0 minus. So, they will produce a vector half the magnitude like this, and again here 0 plus 0 then minus 0 minus. And once again I have here minus 0 0 0. So, I can look at minus 0 0 and 0 plus plus, and there is another one this is 0 0 plus minus minus 0 and I can do this here it is plus 0 plus 0 minus 0.

So, if you know the voltage vectors corresponding to two-level inverter extending it to three-level inverter is quite easy. So, this is all that you have and 0 0 0, minus minus minus, plus plus plus, they produce a null vector. So, the only other vector which are speciality actually three-level inverter are here these are the other vectors. So, I am repeating this number of times for this is useful you know this is plus 0 minus, this is 0 plus minus, here it is minus plus 0, here it is going to be minus 0 plus, and here it is going to be 0 minus plus. So, this is how the vectors are just fairly simple

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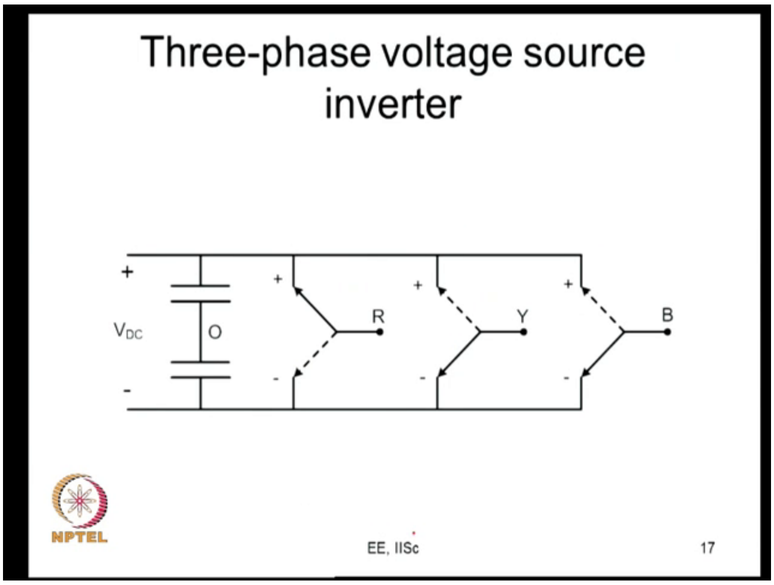

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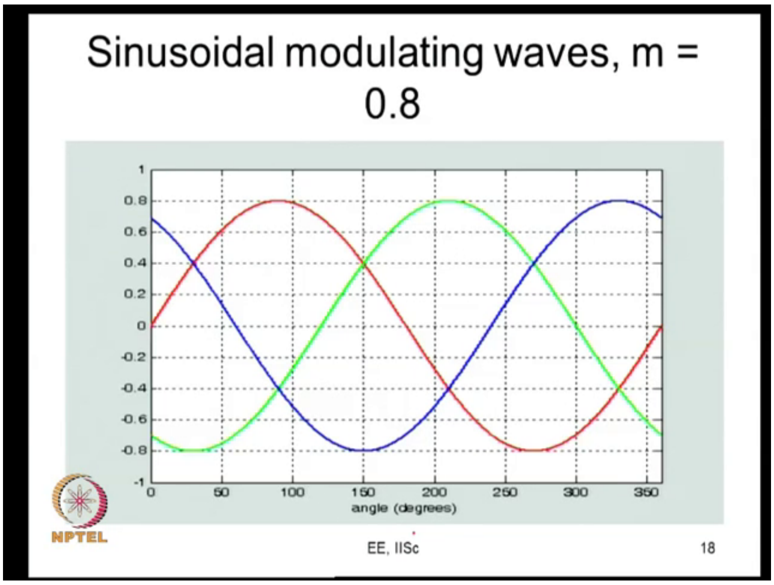

So, if you have a three phase voltage source inverter, you can do a sinusoidal modulation using three phase modulating signals as shown here.

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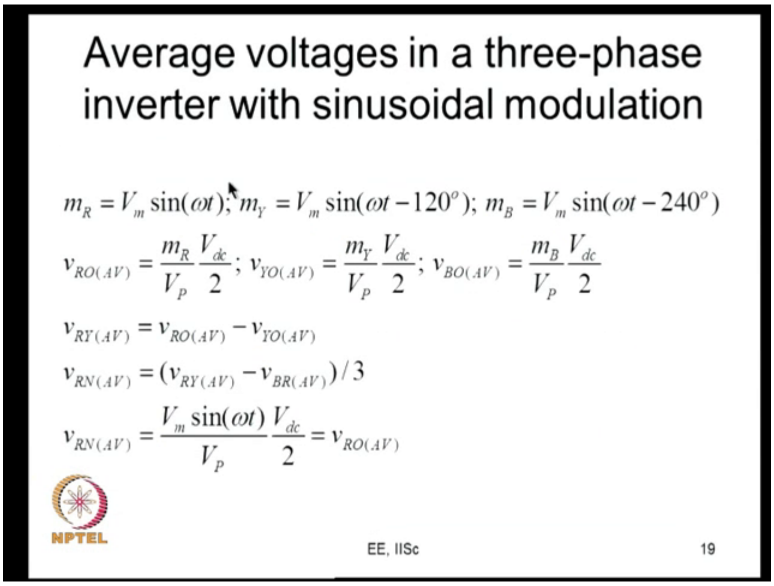

And these would be the average voltages.

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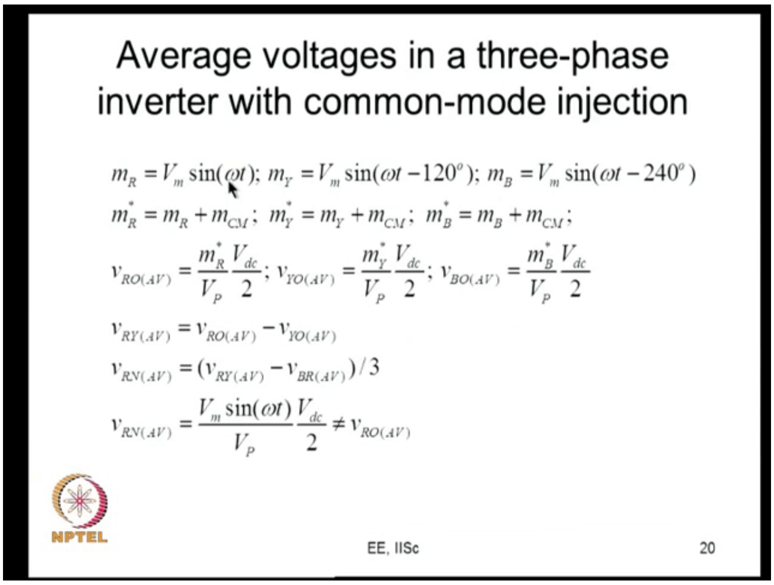

And this is the average voltages when you have common mode added.

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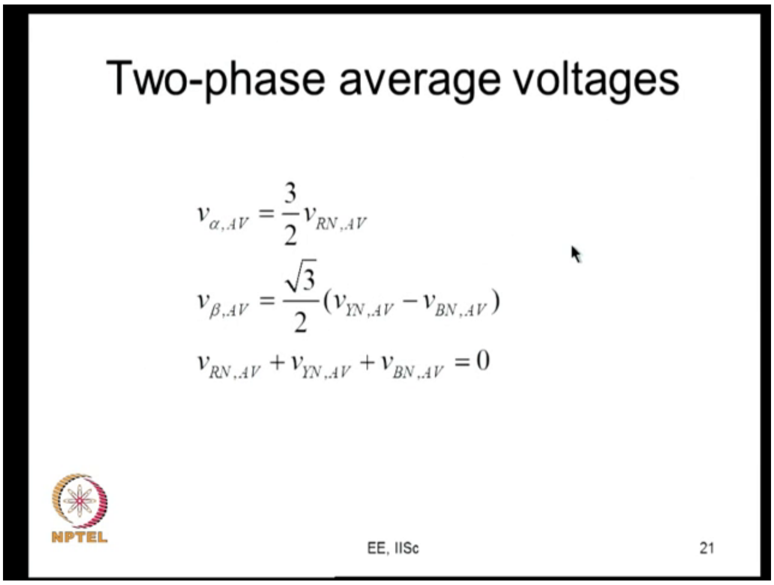

And you know these are three phase average voltages you can come up with the three phase average voltages on the load V R n average V Y n average are the three phase voltage applied on the load. From that we can calculate V alpha average and V beta average.

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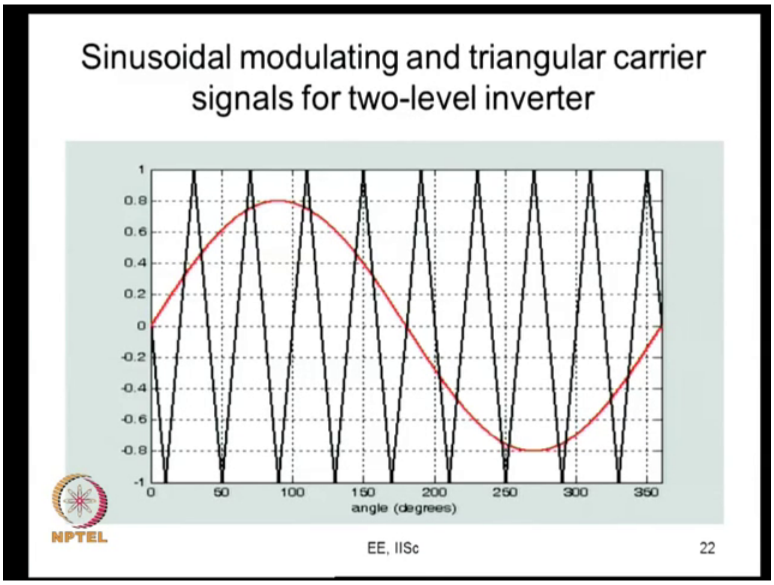

So, all this is possible. So, as we found before sin triangle PWM for two-level inverter you need one carrier.

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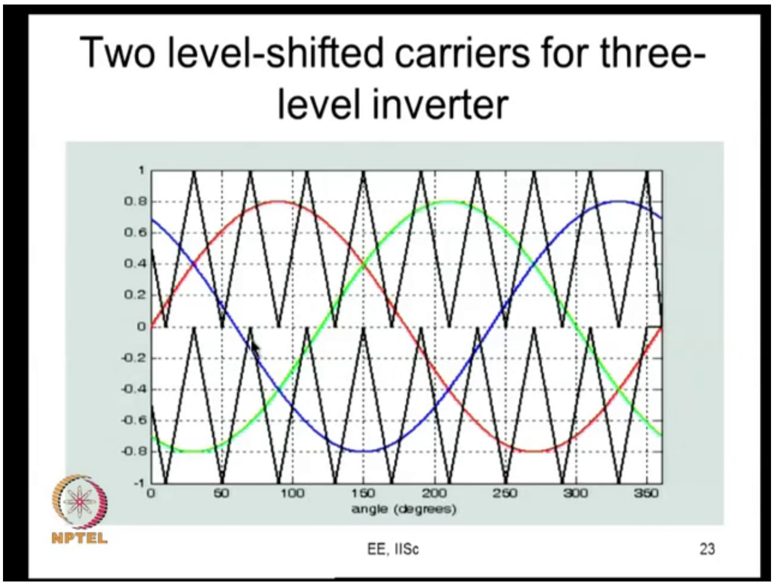

Here you would need two carriers. So, two-level-shifted carriers like this, this is what we do. And of course, as I mentioned to you, you can use only one carrier that is what you can do is shift the R phase signal up by adding plus one to this again whenever this signal goes negative add plus one to this. Again when the signal goes negative add plus one this then you can use only the top carrier for comparison. So, this is something that you use for you know ease of implementation and the result would be the same, but anyway we are considering two-level-shifted carrier wave forms which are in-phase like this for this particular lecture.

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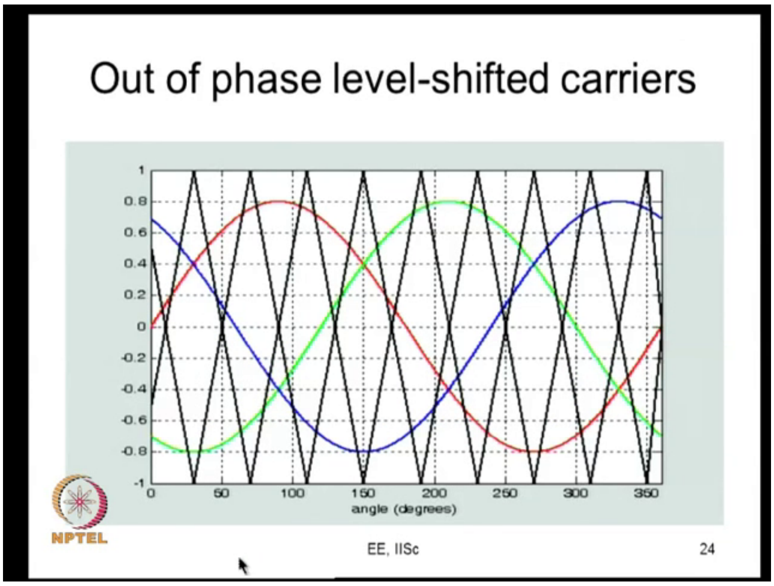

As I mentioned to you already so you can also have a out-of-phase carrier and as we discussed in the last lecture, the inverter state sequences different here. Here you use the three nearest vectors, here you use four different vectors and one of the vector is far away from the reference vector at least one of them. So, the instantaneous error voltage vectors high which is also shows that the harmonic distortion is high, and there some detail study that has been carried out. And there in the references that I indicated to you can find more details on this now.

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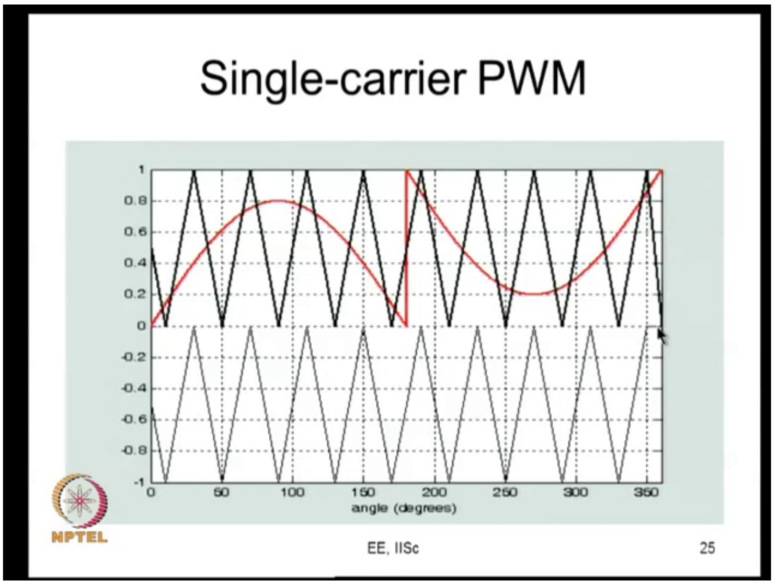

So, what we would actually do is see this is what we will do for the implementation will we will shift that, but you will consider the carrier to be two-level-shifted carrier compared with the sign or any other modulating signal here.

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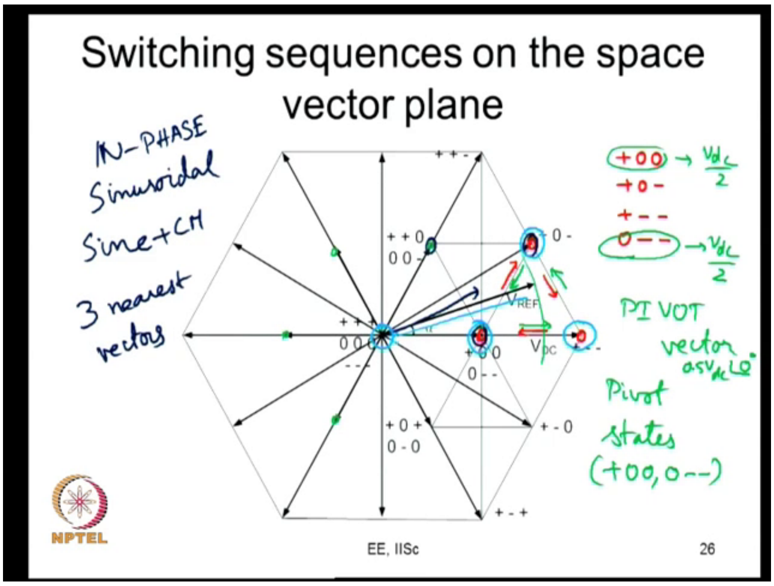

So, when look at the switching sequences in the last lecture what we found out was let us say if you are looking at the in-phase triangle PWM, it starts from here. So, for some set of three phase references, it could start from plus 0 0, it could go to plus 0 minus, plus minus minus and come back to 0 minus minus like here and back here. So, this is something these three vectors and it starts from here and comes back here. Let me just indicate it in terms of arrows. So, it may go like this.

Again in the opposite direction, so what happens is when the reference vector is sweeping through this region, when the reference vector is sweeping through this region you know you can talk either in terms of reference vector or three phase sinusoidal modulating signal. If you have modulating signals, you transform them into the space vector domain it becomes a reference vector you see this plus 0 0, you see 0 0 minus, both of them lead to vectors of length V dc by 2 and the same vector. So, this vector you call that as the pivot victor because you know generally you know it starts from there it ends from here. And you call those two states as the pivot states that is you call those two states as the pivot states, what are the pivot states plus 0 0 and 0 minus minus.

Similarly, this is also pivot state, these are all pivot states there is a terminology that we generally use here now. And pivot vector is like when you say it is 0.5 V dc angle 0 that is the pivot vector we are talking of that can be realised using two states. And now you see this is the redundancy I was telling you this is the kind of redundancy you had in a two-level inverter you had two different states, now you have two different pivot states. So, this gives you lots of possibilities now.

So, in the case of sine triangle PWM, what happens is you start from here and come back and go on there. With some common mode addition the time you spend at plus 0 0 or 0 0 minus change, but the total thing does not change, it is just very similar to common mode addition in the case of two-level inverter. So, you can add common mode to this, this is what we saw. And if you have common mode then these two times will change, so that will happen you know you still get the same vector. Again if you are let us you are in a different vector like and let me just indicate something else.

Let us say different color maybe. So, if you are tip turns out there you will see that you know will see for certain sets of three phase references, you will see that these three are getting applied and you will find that your reference actually falls somewhere in between. So, in-phase sin triangle PWM and you know where you use this in-phase carriers level-shifted carriers, you may compare them with sinusoidal modulating signals or you can have sine plus common mode. In all this cases, you generally find that the three nearest vectors get applied. And therefore, they lead to good harmonic performance.

Particularly when you go to conventional space vector PWM you make sure that these two get applied for equal duration of time and that makes the harmonic performance a little better than what is possible with usually with sin triangle PWM. On the other hand, when I talk to you about this method you know the out-of-phase the out-of-phase would use these sequences which I am circling using blue. And you can see the error is pretty large for example, when this is applied this error is pretty large here and therefore, it produce higher amount of harmonic distortion.

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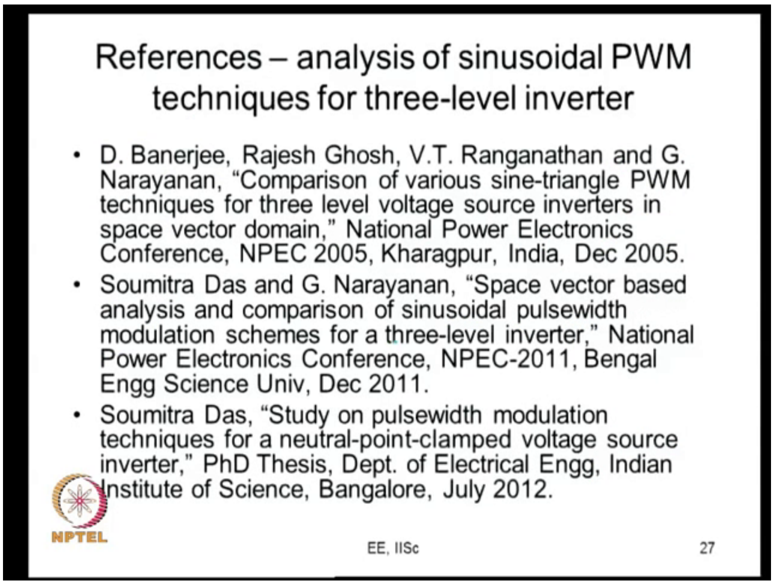

So, as I mentioned to you these are some good you know papers I mean this are some useful references for you to understand this subject I mean for this in-phase and also out-of-phase sin triangle PWM and also look at some other triangle comparison methods and try to analyse them.

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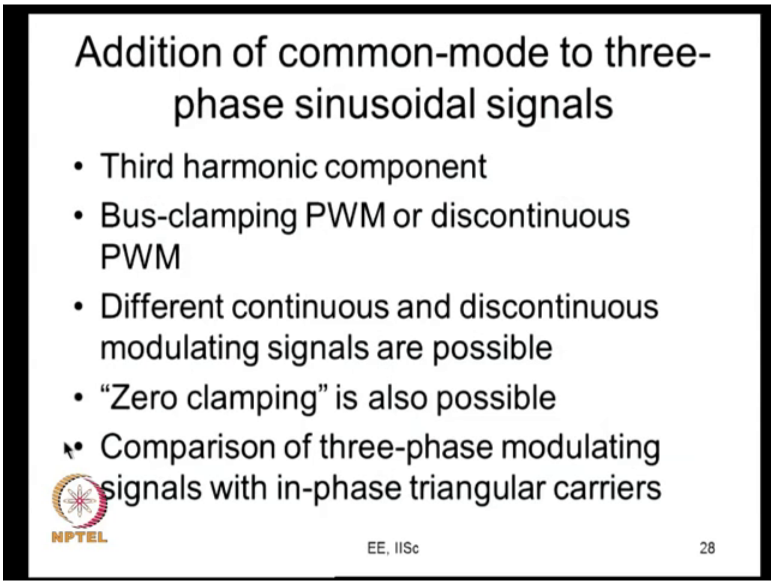

So, as I mentioned you know through three phase sinusoids you can add third harmonic component and you can add suitable common mode component such that the PWM in the phases would be clamped PWM you know to one of the buses. So, you can have different continuous or discontinuous modulating signals as you have in two-level. In fact, more possibilities are there.

For example, here 0 clamping is possible as I mentioned towards the end of the last lecture that is in two-level inverter you can clamp phase to the positive bus or to the negative bus. So, you will clamp it for the positive bus in the positive half cycle for 60 degree, and clamp it to the negative bus phase to the negative bus during the negative half cycle for 60 degree. Now, you can actually clamp a phase to the 0 bus that is a dc midpoint for 60 degree in the positive half cycle, again for another 60 degree in the negative are cycle. So, such as interesting methods exist that is what you would you call as 0 clamping PWM for example, you call them like that is also there now.

Then you have comparison of three phase modulating signals, but what we assume in all this cases we assumed different continuous and discontinuous modulation signals. But we assume that we are using in-phase triangle or carrier only which essentially ensure that we are getting the three nearest vectors and the common mode make sure that the pivot state times the division of pivot state times changes. And if you go to bus-clamping what happens only one pilots state is used, the other pivot state is not used, so that is what happens now.

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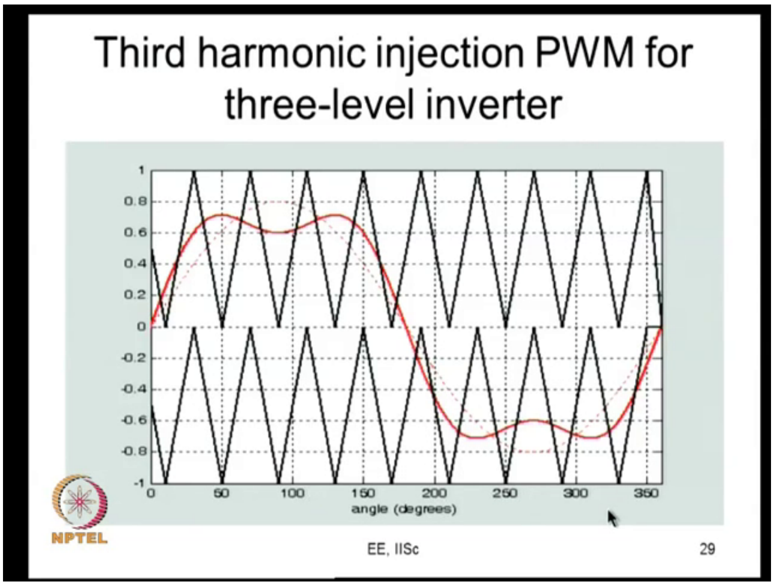

So, as I said with third harmonic injection the switching sequence will be pretty similar to what we did with sine triangle PWM.

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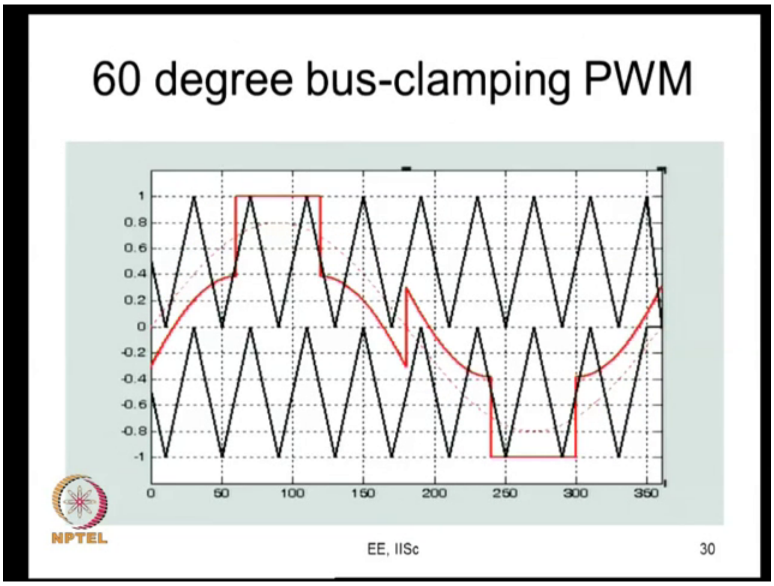

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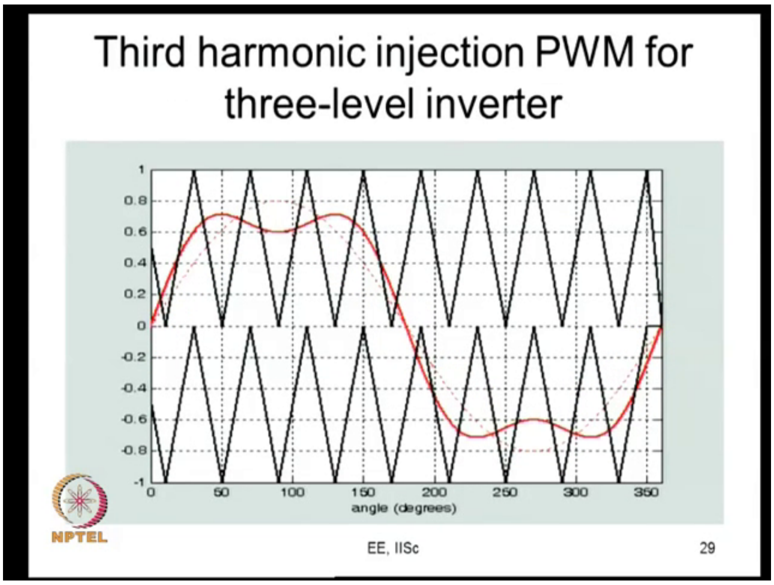

Sequence will be the same the pivot state times would slightly change because of you know in common mode addition now. So, you are R phase signal here for example, is come down. So, here you know have. So, Y and d phase would also come down by the same extent. So, you will find that a one particular pivot state is applied for longer than the other and the other one would get applied for shorter time. So, this addition of common mode changes the pivot state time the total pivot vector time is not changed, but the division of pivot vector and between the two pivot states is changed.

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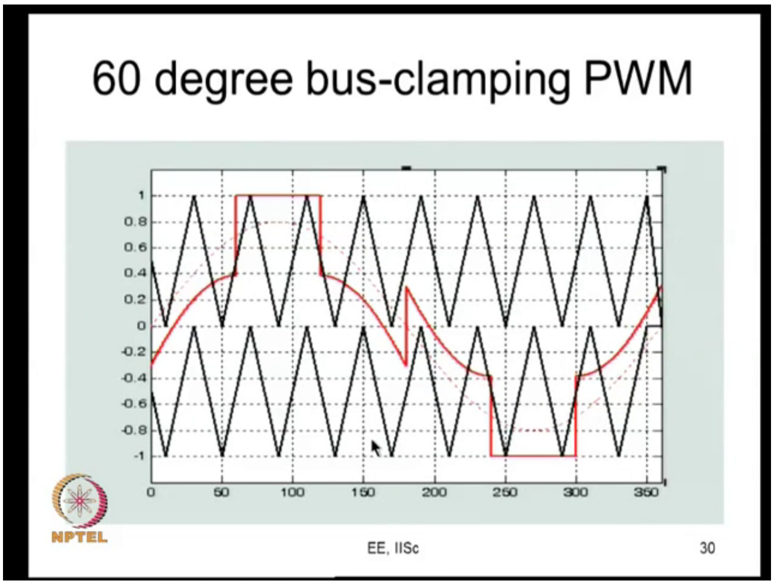

Now, you same kind of 60 degree clamping we use know we looked at continual clamp and split clamp PWM methods for two-level. Here also you can look at continual clamp

PWM wave forms modulating wave forms where a phase is clamped continuously to the positive bus for 60 degree. And continuously to the negative bus for 60 degree and here it is you know between 60 to 120 degree in the middle of the positive of cycle here again its middle of negative cycle it is not necessarily. So, this can be anywhere the this can start anywhere from 30 to 90 and the clamping region can end, anywhere between 90 to 150.

And this can be symmetric like this can start anywhere from let us say 210 to 270. And this can go on all the way till 270 to 330, so that would be continual clamp PWM and sixty degree bus clamp PWM is one specific example. So, you compare it with two-level-shifted high frequency carrier. So, you will see the R phases clamped here and here again also R phases clamped similarly you will have other regions where Y and B phases will clamped out just one example I am giving there are many, many possibilities, every possibilities that existed into two-level also exists here and more number of possibilities exist in three-level inverter now.

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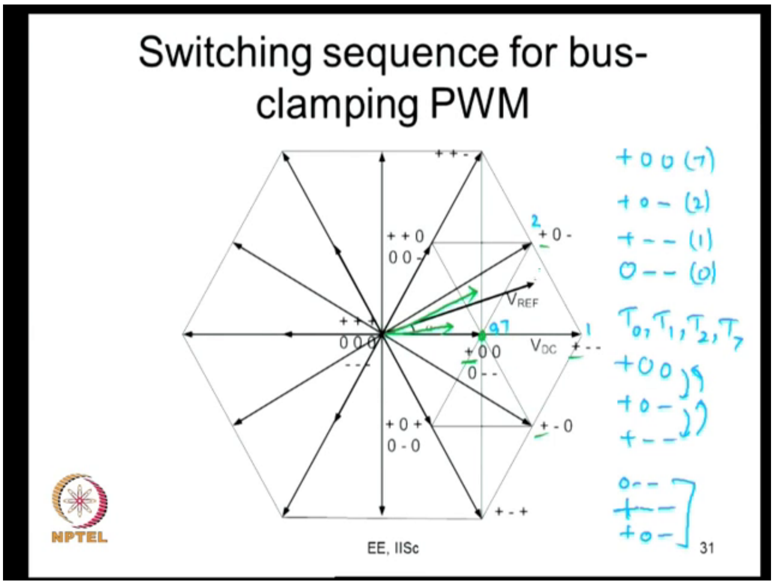

So, when you do this I am sorry. So, what happens to the sequences you end up with the same set of sequence as I mentioned before like you can work that out. So, for this if we start with plus 0 0, go to plus 0 minus, plus minus minus, and go to 0 minus minus. So, for our question of convention let us call this is 0, let us call this is 1, 2 and this is 7 like we called in a two-level inverter. So, this is 0, this is 1, this is 2, and this is 7. So, you have these vectors applied for a duration T 0, T 1, T 2 and T 7. Now, if you consider the same sinusoidal reference and add some common mode to that the V reference vector will not change because the common mode signals are added V reference vector does not change now. So, the V reference vectors continues to be same, but what you will find is when you compare this is the time for which this T 7 may reduce at T 0 may increase or vice versa, so that is what you will happen.

Now, as an extreme case for bus-clamping PWM what will happen here is one of them might not be there. For example, you may have only plus 0 0, plus 0 minus and plus minus minus, and the same thing may had go in the opposite the reverse direction. Or it could be the other way 0 minus minus, plus minus minus and plus 0 minus this what you will find in bus-clamping PWM, one of the pivot state is not used. You can find some similar observations when you use let us say here also like you have a different sets of three phase modulating signal, the equivalent reference vector may fall here or you may have equivalent reference falling here.

In all these cases, this would be the pivot state and in this pivot state I mean pivot vector and you will see that only one pivot state would get applied if you are talking of bus-clamping PWM. And for the kind of bus-clamping PWM, I showed you this middle 60 degree R phases positive and therefore, this will not get applied R being you know R being positive is what will actually get applied a I mean make sure that you know R phase is always positive only such inverter state would actually be applied now.

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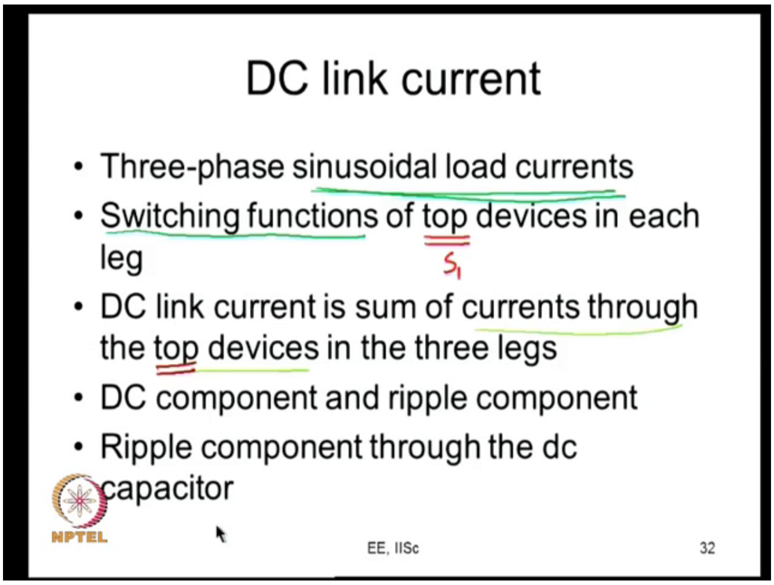

So, you know everything that we studied there can be extended here also. So, in the case of two-level inverter, we considered three phase load currents to be sinusoidal, the harmonic neglected. Here also there is harmonic are neglected, there is still greater reason to neglect harmonics here because the three-level inverter produces better way from quality than that. Then like before the switching functions we have to multiply the load current with switching functions, but the difference now is the switching function of top device earlier, there is only one top device and one bottom device in a two-level inverter.

Now, here you have S 1, S 2, S 3 and S 4 and by top device here I mean S 1. What I mean here is S 1. So, for R phase like it would be S R 1, S Y 1, S BN. So, you have to multiply by the so switching function is common there and here you have to multiply it with switching function, but which switching function it is a switching function of the top device here. Again then the next thing what you do is you find the currents the top device currents the currents in the top devices as in the previous case, the only difference is that it is top that is a difference. And if you add those three you would get your dc link current, so there is similarity except that you are going to multiply it by the switching function and then the top device currents are going to be added.

So, once you that you will get the dc link current, so the dc link current as before will have a dc component and it also have ripple component. And this dc component will flow from the rectifier or the dc supply. And the ripple component you would expect most of the ripple component flows through the dc capacitor, some part can come from there also, but many at times you can assume the entire ripple component flows through the dc capacitor and you can go, but evaluating the capacitor current the dc capacitor current.

So, you know the same way like you know just a little more complex more involved than two-level inverter, otherwise you can do it in the same fashion. So, you can once again come up with the RMS and the capacitor current which will help you in sizing. And once you have the R m s current you can also estimate the power loss along with the knowledge of the equivalent series resistance, and with power loss you can estimate the temperature rise and also possibly the life of capacitor.

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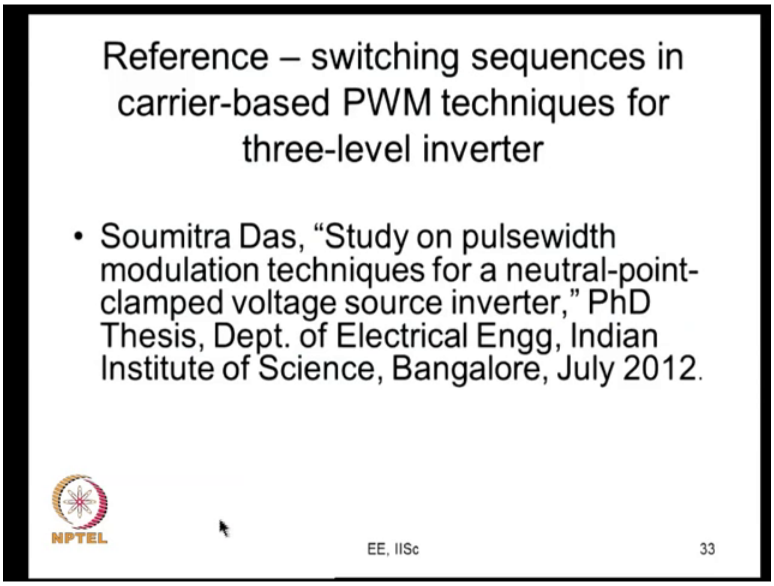

So, you can actually you know it is not a about the dc link current, but the rest of the things you can actually you know for switching sequences for various carrier based PWM and all that you can actually look at this thesis as a reference now.

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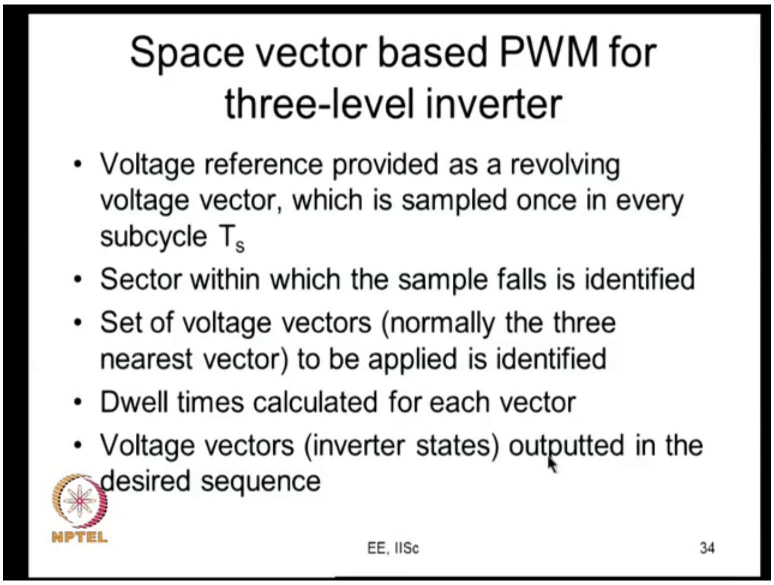

So, let us look at the doing things from the space vector at a point of view that something that what we have to look at. That is what we are doing is we looked at the three phase references being provided as three phase sinusoid or three phase sinusoid with common mode added. Instead what we will do is it will consider the reference as a voltage reference being provided as a rotating reference vector. So, revolving reference vector which revolves at the fundamental frequency omega and its amplitude or its magnitude is proportional to the fundamental voltage we want. And this we are sampling once in every sub cycle T s, this is similar to what you do in a two-level inverter, space vector based PWM for two-level inverter.

Then you identify the sector within which the samples falls, again same as what to do in two-level inverter. Now, the only difference is the set of voltage vectors to be applied should be identified. In the two-level inverter, it is normal you know it is the two active vectors one on the clock wise side of the reference vector the other on the anti clock wise vector. So, two active vectors and 0 vector here you can consider different sets of vectors actually speaking. And you normally consider the three nearest vectors now.

And finding this three nearest vector is some additional job that you really have to do and that takes certain amount of computational effort now. And once you do that for each of the three vectors for example, let say we have identified the three nearest vector for each of the vector you have to calculate the dwell time. And what can I actually happens depending on where you are the formulae may have to be used could be different, and after that you go about out putting the voltage vectors in the desired sequence.

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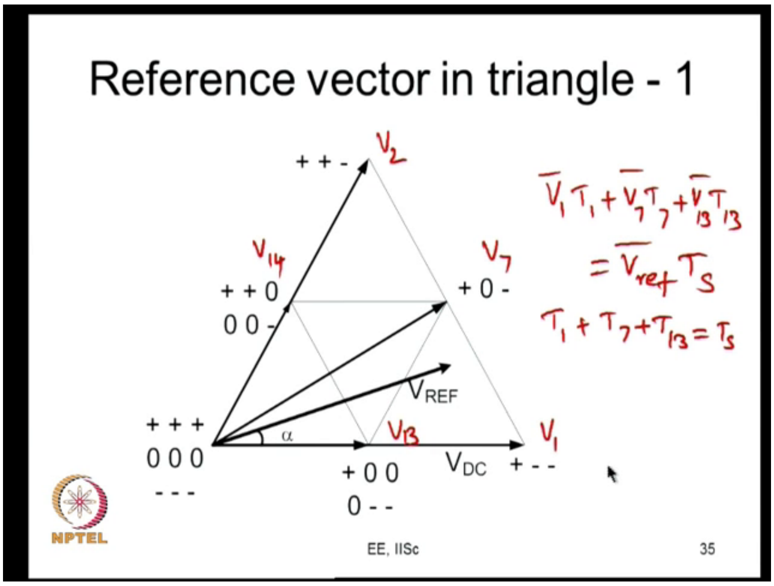

So, let us say you are like this now you have identified now that is the rotating vectors which has been sampled and you identified that this falls in the so called sector one. Now, in the sector one the tip falls in a so called triangle one let us call the this is triangle one. So, sorry this is this is triangle one formed by these three vectors now. So, these are the three nearest vectors now. So, you are going to do some calculates lets gives some let us give some names here this is it called as V 1 vector, let us call this V 2 vector as before. So, let us call this is V 7 vector. So, let us call this as the V 13, let us call this as V 14 vectors.

Now, what you have to do is V 1 vector T 1 plus V 7 vector T 7 plus V 13 vector T 13 equals V reference vector T s, this is the old second balance equation. This is a vector equation, so it contains two equations. Then the other equation as T 1 plus T 7 plus T 13 equals T s the idea of old second balance is still the same you need three vectors now you use three vectors. Now, you what you see is actually the three vectors have to surround the tip of the reference vector that is important.

You can actually use these three vectors also these are the three vectors you would have used as a two-level inverter. So, now, you have another set of three vectors and these are closer to the this vectors and therefore, the error vectors are closer and therefore, the integrals are going to be lower and therefore, you are going to have lesser amount of distortion here current, so that is the basic difference. Now, but you have to calculate this T 1, T 7, T 13 by a solving this you will get some set the formula in terms of V reference and alpha you will get a you know T 1, T 7 and T 13 you will get some set formula if you really sit and do this now.

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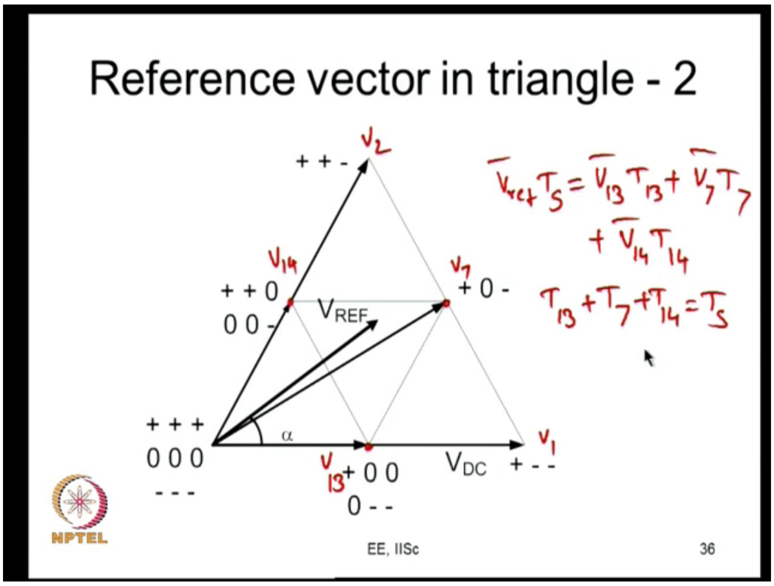

So, now let us say the reference vector was not here, but the reference vector is here. So, what now you will have to use these three vectors. So, let us say we call this V 1, V 7 this is V 2, this is V 13, this is V 14. Now, V reference vector multiplied by T s this is the desired volt second that will be equal to V 13 vector T 13 plus V 7 vector T 7 plus V 14 vector T 14. Then you have T 13 plus T 7 plus T 14 is equal to T s this is from solving this you get the volt second balance this is the volt second balance then you can get expressions for T 13 T 7 and T 14 in terms of V reference and alpha. But you will see that these two expressions, this set of formula that you get from here and set of formula you get from here would be different, this is one difficulty you have.

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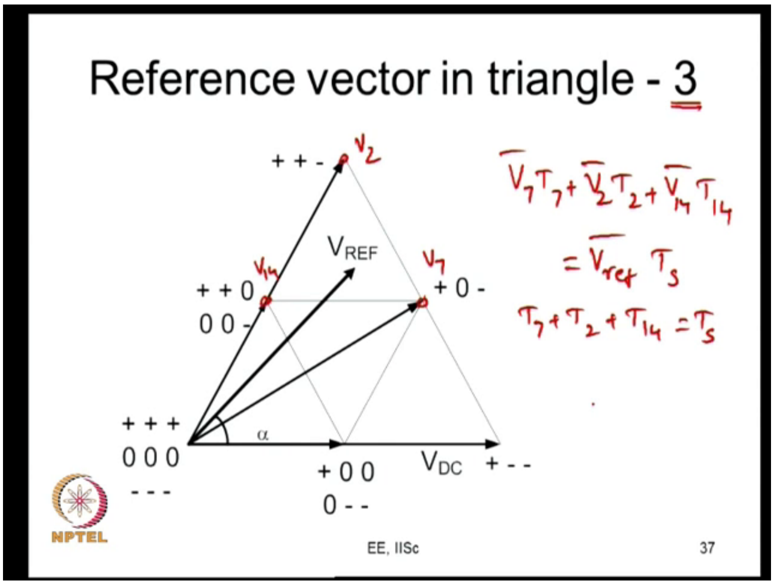

Now, once again let us say you have here if your reference vector falls in this so called a triangle three, what you need to do now was this is V 7, this is V 2 and this is V 14. You say V 7, T 7 plus V 2 T 2 plus V 14 T 14 equals V reference T s the idea of volt second balance is still the same, but the choice of vectors is different. So, you have T 7 plus T 2 plus T 14 is equal to T s this will give you another set of formulae for calculating T 7, T 2 T 14.

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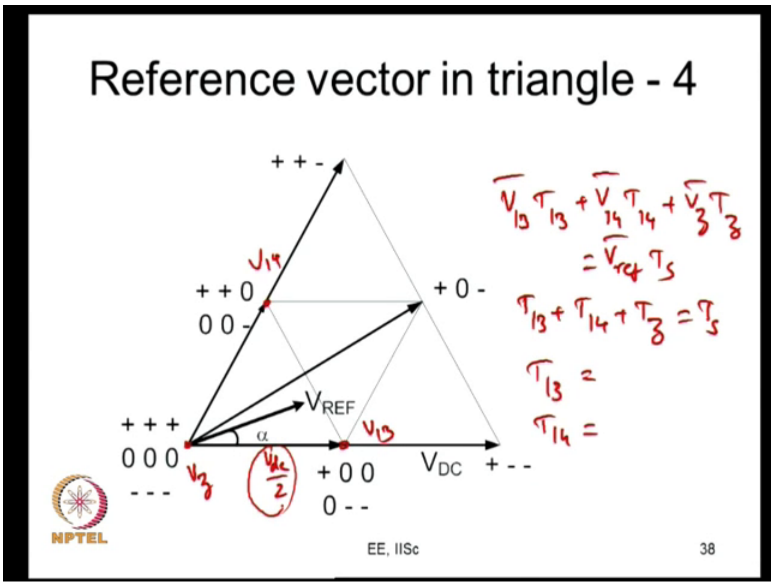

And here this is pretty similar to what you have in a two-level inverter except that this dc voltages here I mean the voltage vector length V dc by 2. So, once again what you will get is if you call this as V 13, you call this as V 14, and you call this as V z, you have V 13 vector T 13 plus V 14 vector T 14 plus V z vector T z is equal to V reference vector T s. And T 13 plus T 14 plus T z will be equal to T z. So, these are all will be different and that is going to pose a difficulty. And then this if you if you write down the equation for T 13, T 14 and T z, you will find them pretty similar to the two-level inverter case except for V dc will now be equal to V dc by 2, this is the difference that you have now. So, when it is in this four different triangles, you have four different formulaes. So, there is some difficulty.

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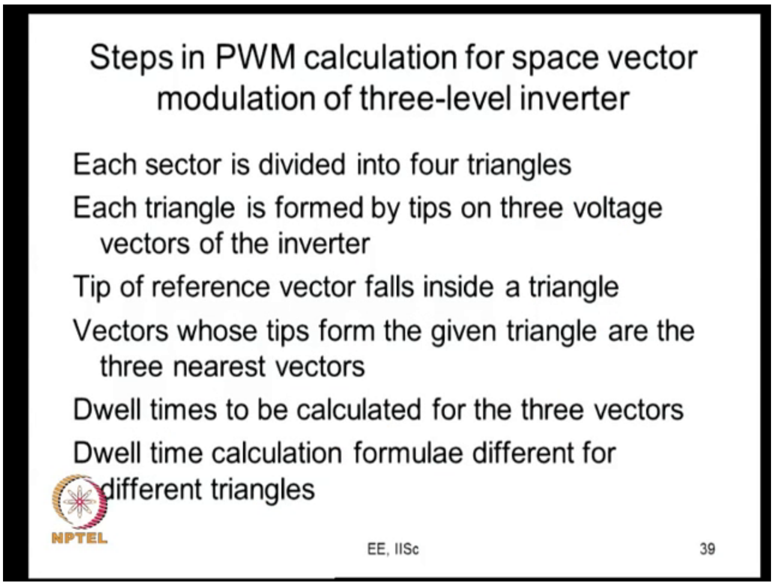

What is normally done is you reduce that to an equivalent two-level inverter. So, these are the difficulties. Each sector divided into four triangles and each triangle is formed by the tips of three voltage vectors, and you know you have to see which vector where it falls and then calculate the dwell times for those three vectors and you have need different formulas.

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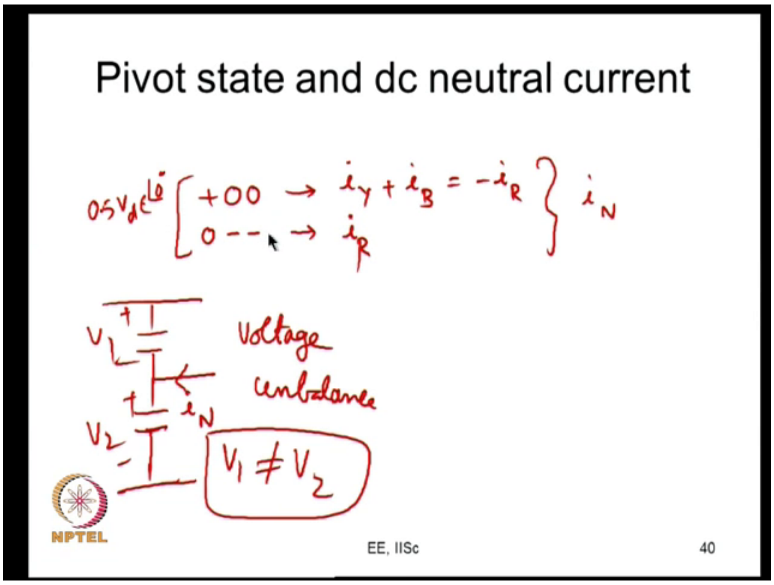

To solve the problem, what you actually do is to deal with the an equivalent you know two-level inverter. So, before that let us take a quick look at the pivot states which is really our you know there is plus 0 0 0, and 0 minus minus, both of them give your same vector which is 0.5 V dc angle 0. So, now, if you look at there is current flowing to the dc neutral there is a current flowing into the dc neutral. So, how much is that current flowing into the dc neutral, in this case, i Y plus i B which is equal to minus i R is the current flowing into the dc bus midpoint when you are applying this state it is i R is the current that is flowing into the dc bus midpoint.

So, what you see is you know as for as the load is concerned in the another load voltage is concerned this state and this state do not make any difference at all, they produce same set of line-to-line voltages. But as far as the inverters they make a difference this is something I have been mentioning in a two-level case also, there it would make a difference in terms of who is conducting conduction loss and switching loss, here also that same thing is valid. One additional thing is that the current is flowing through the dc bus midpoint which is in a two-level inverter the connection it does not exist at all, whereas in a three-level inverter that connection exist therefore, there is current flows.

How much current flows in this case the current flowing is i Y plus i B which is equal to minus i R. Here 0 minus minus R phase is connected to the dc midpoint therefore, R is Y. So, you can see that opposite values of current I mean equal magnitude, but opposite sign follows there. So, they actually have opposing effects on the dc voltage unbalance this dc current flowing through that what will it cost if for example, let say you have this dc, you have this. Now, through this midpoint some current flows there is some current flows that is called as i neutral call this as i n for i neutral and this is going to charge or discharge you know in some particular direction. And this is going to lead to voltage unbalance that is this voltage V 1 and this voltage V 2 may not be equal this causes this problem and the problem is because load current is flowing.

And one way to do this is you can look at how they are unbalanced. And you can see that these two have opposing effects on that one injects current i R you know injects current minus i R. So, the choice of pivot state is also know you know that if this is the cause for voltage unbalance and this can also be a possible solution for voltage unbalance. You use one state more and other state less, you have this choice you can still produce the same reference vector. So, the choice of the pivot state can also be used to some extent to meeting at this voltage unbalance is this is one of the point I wanted to tell you.

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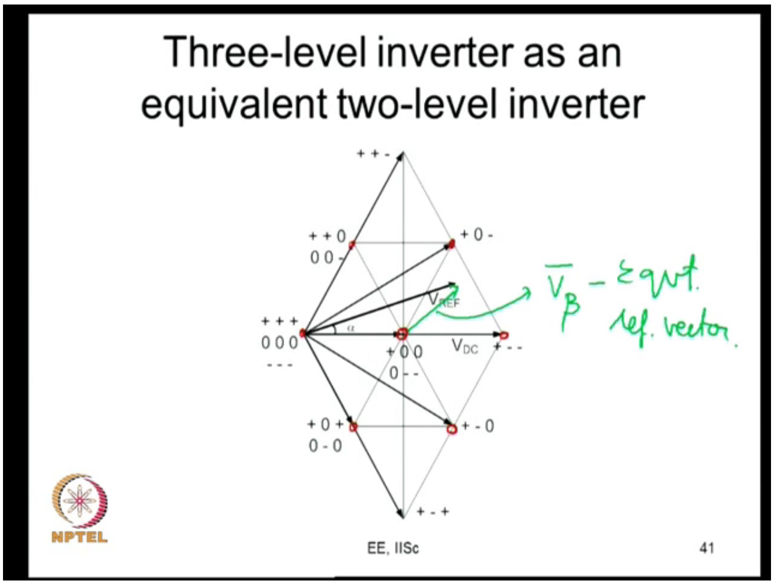

Now, coming back to what we are trying to do this is I am showing a part of the picture I am not showing all the six sector, but I am showing only this region now. So, if you look at there are certain things we can always observe. Let us say the reference vector is only within this part, this is reason somewhere within this. So, you will see that the R phases predominantly positive, this is R is 0. And you will see that the Y phase is predominantly switches between minus and plus whatever you know that there are there some limited thing.

So, let us say here. Now let us look at this hexagon let us look at. So, this pivot vector is very similar to 0 vector in many cases and therefore, you can look at this hexagon and this hexagon is quite similar to that of a two-level inverters hexagon. So, what you can do is in every extend you can regard this as an equivalent two-level inverter. Now, this is your pivot vector. If you subtract the pivot vector, you are going to get some vector let us call this as some V beta vector. So, this V beta vector is the equivalent reference vector for a conceptual two-level inverter you can view this as a conceptual two-level inverter.. Let us come back to this in a different fashion now.

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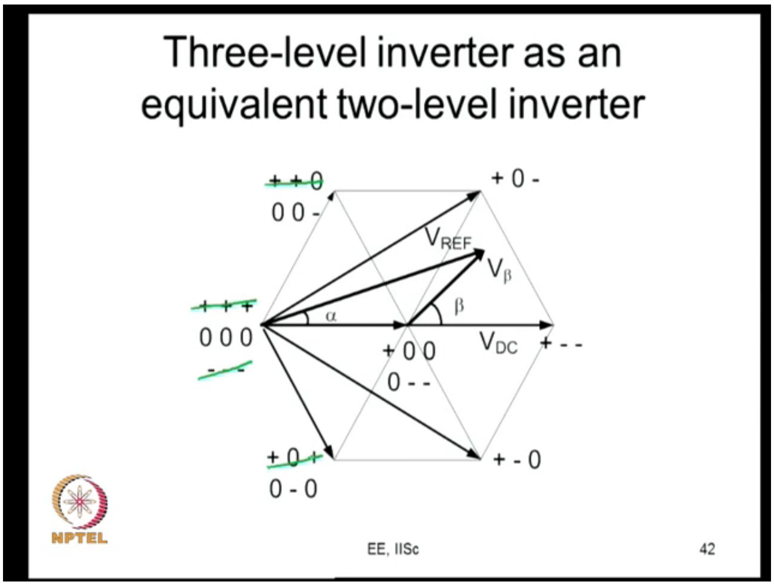

So, here I am just trying to show that sector alone, I am just trying to show that one alone. I am showing only that hexagon which I had shown in the previous picture, I will remove this portions and showing this now. I have subtracted and showing this V beta vector and this is at an angle beta. Now, if you look at this it is very, very similar to a two-level inverter, this is plus 0 0, and 0 was 0 minus minus are like your 0 state plus plus plus and minus minus two different 0 states and there are active states here. The only difference is there are more number of states here and you will see that many of them may not be used plus 0 minus, you make one switching you would go to 0 0 minus. And from 0 0 minus you would go to 0 0 0; from 0 0 0 one switching will lead you to 0 minus 0, and you go to plus minus 0, some of them you will not use, so actually this is what you get.

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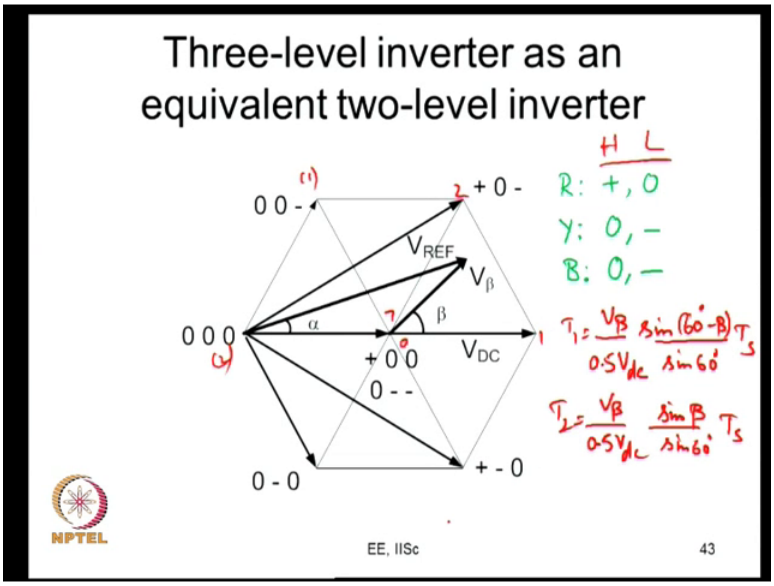

Which ones you will not use here this one is something you may not use. So, these are the ones that you really use you here now what it is really happening if you look at R phase the R phase is either plus or 0 you look at Y phase Y phase is 0 or minus you look at B phase it is again 0 or minus.

So, this is what you get in all these six cases that is what you are trying to say. Yes, let me argue differently R phase is there right, there are three voltage levels plus V dc by 2, 0, minus V dc by 2. Now, this is the part is the positive half cycle of R phase this part is positive half cycle of R phase. So, your fundamental voltage R phase fundamental voltage positive. So, there is no business for the R phase really to go to minus it is usually going to switch between plus and 0 only.

So, let us say R phase switches only between plus and 0. Now, let us take Y phase up to this angle this is the Y phase 0 crossing actually Y phase is negative here when Y phase fundamental voltage is negative you want to switch the Y phase only between 0 or minus Y phase does not really have to switch to positive. So, in its negative half cycle it is only between 0 and minus and again you take B phase B phase is negative peak is here and this is part of the B phase negative half cycle. So, B phase which is only between 0 and minus.

So, what we are trying to say is let us say the particular phase which is only between plus and 0 in the positive half cycle and 0 and minus in the negative half cycle. So, based on this you can divide the entire fundamental cycle into six extends. So, in each extent you know you will find that you know for example, this is one extent. In this extent, you will find that R is switching only between plus and 0 Y is switching between 0 and minus Y, B is also switching between 0 and minus. So, you can call this high and low, high and low, high and low. So, you know you ignore plus and 0 for the time being.

So, you see that this three-level inverter is really like a two-level inverter, because the inverter never getting connected to the third level within this region. So, what you do is in every region you start looking at the inverter as two-level inverter; but the high corresponding to R phase is plus; and low corresponding to R phase is 0 here. But when you look at some other region here the high corresponding to R phases will be 0 and the low corresponding into R phase will be minus. So, this will change what is high what is low that will change. So, this is high and this is low this definition will change, but within one extent you can always look at that as two-level inverter. So, this is something that you can commonly use.

So, you use V beta now this V beta it is it is easy like a two-level inverter this angle beta tells you in which sector it falls you can call this is the sector 1, 2, 3, 4, 5, 6 like your older case. And then you know these vectors and now your calculation is same you know you can calculate your null vector time in terms of V beta and beta it is going to be V beta by 0.5 V dc multiplied by sin beta by sin 60 into T s that is going to be this active vector time. This active vector time is going to be sin 60 minus beta.

So, I can write it down if you necessary say you call this 0, 1, 2 and 7, T 1 will be V beta divided by 0.5 V dc instead of V dc it is now 0.5 V dc and sin of 60 minus beta instead of sin 60 minus alpha divided by sin 60 into T s. And T 2 will be V beta by 0.5 V dc sin beta by sin 60 into T s. So, this formula would be the same. So, you know your definitions are always like this. So, you would call this as 1 and you would call this 2 in this sector for example, you can actually calculate like this. So, the calculations become much simpler now.

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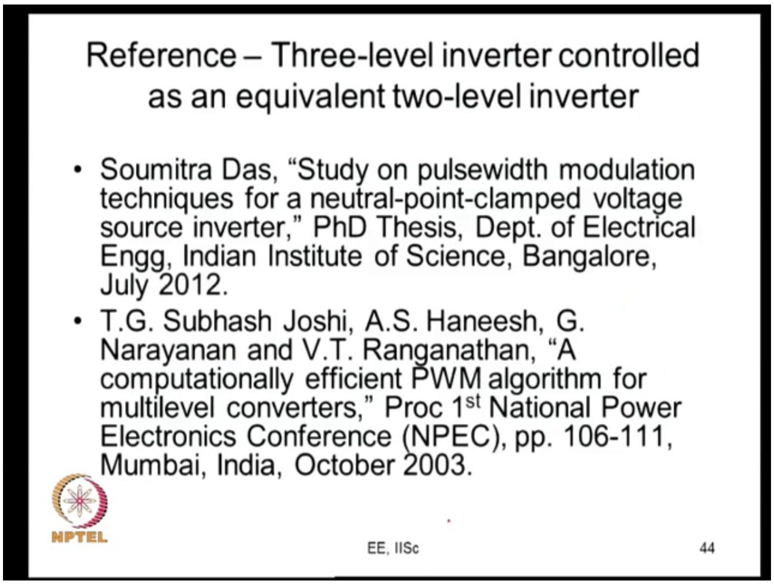

So, there are many easier ways of implementing, it has actually been discussed extensively in the literature. This one particular paper is one way of implementing the centre space vector PWM, you know the conventional space vector PWM which you know involves the null vector time or the pivot vector time to be equally divided this is one reference for that. This see you thing of seeing three-level inverter as in equivalent two-level inverter has also been discussed extensively in this particular thesis now.

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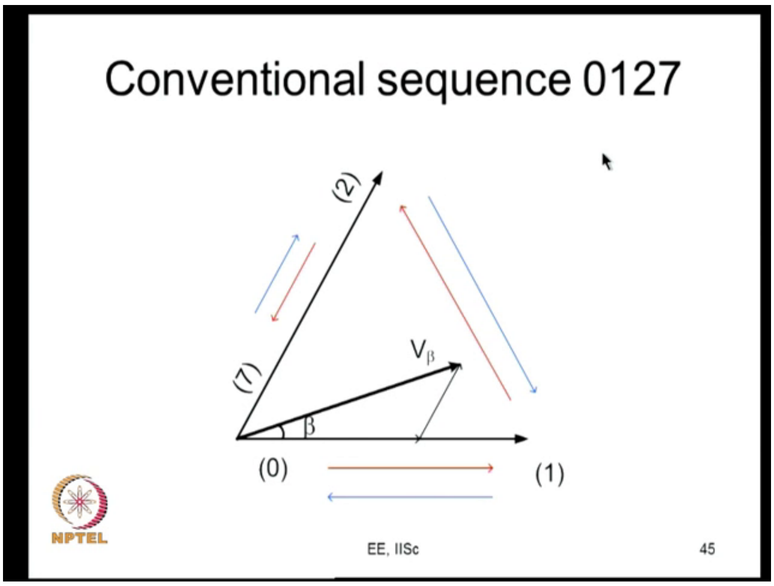

So, once you break it down to two-level inverter, many of our other relatively newer ideas and ideas on switching sequences can actually be taken over to a three-level inverter. Now, you have the conventional sequence. What you do you start from 0127? So, this is the equivalent reference vector V beta with angle beta for that. So, what you really do this you, you apply you know 1 and 2 for certain durations T 1 and T 2 and T z for the remaining duration, so that you realise this.

So, you can apply this whatever is your T z you can apply T 0 and T 7 for equal durations of time as in conventional case you start from 0127 this is your conventional sequence. Where 0 is one pivot state, and 1 is some other active state, two is another state and 7 is your back to your pivot state. So, you are starting from pivot state and ending here; again you are going in the opposite direction. This is the conventional sequence extended to a three-level inverter now.

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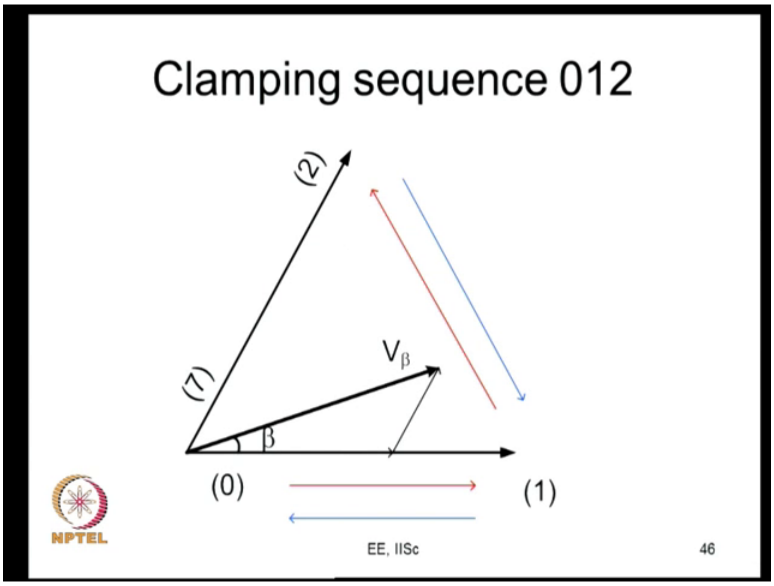

The same way the bus-clamping sequence 012 can be extended now. So, let us call one of this pivot states 0, this is 1, 2 and the other pivot state is 7. You start from 0, you apply the same pivot state for the entire pivot vector time then this is T 1 and T 2 that is all. You apply this for T 2 seconds come back apply for T 1 seconds and come and stay here for T 0 second that is conventional sequence 012 you. So, 012, 210, you can go around like that.

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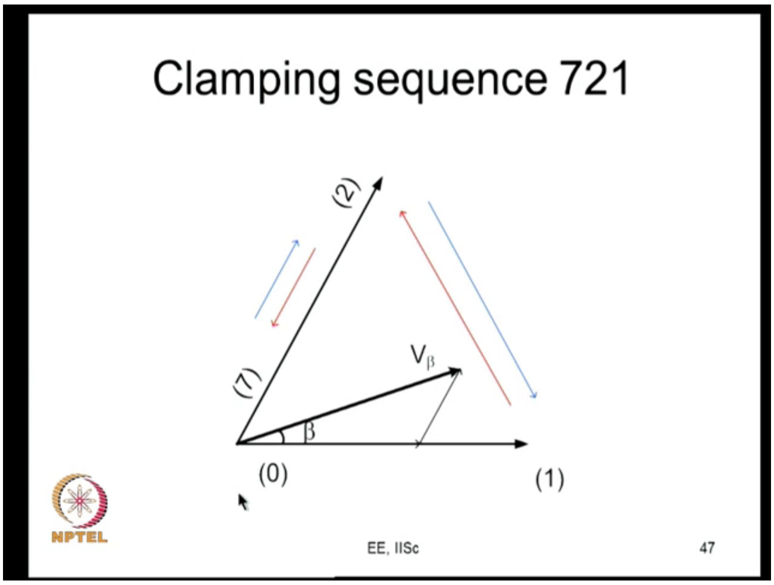

The same way you can do the other clamping sequence also that is you are now avoiding the pivot state 7, you start from 721, 127.

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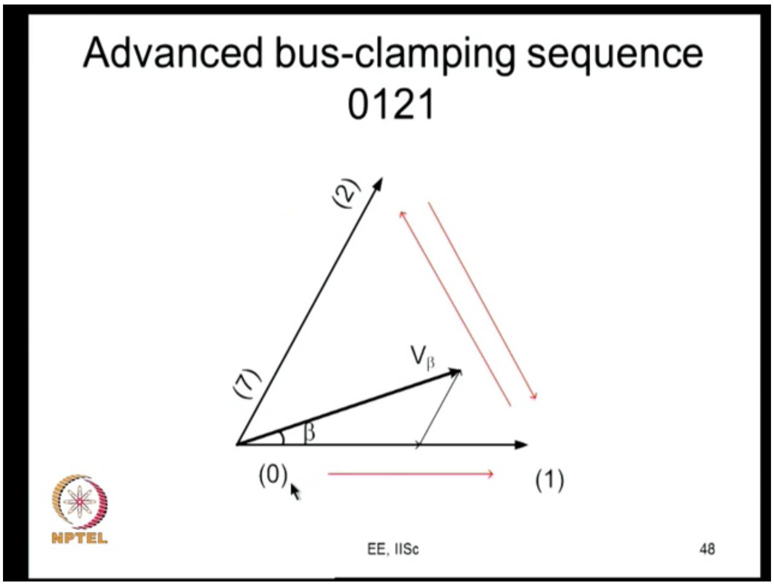

The same way you can go to the advance bus-clamping sequence also. You avoid this pivot state 7, so 0121. You apply this 0 for the entire pivot vector time T z apply this for T 1 by 2 sector seconds go here stay for T 2 seconds come back and stay here for T 1 by 2 seconds. And you can do the reverse again 1210.

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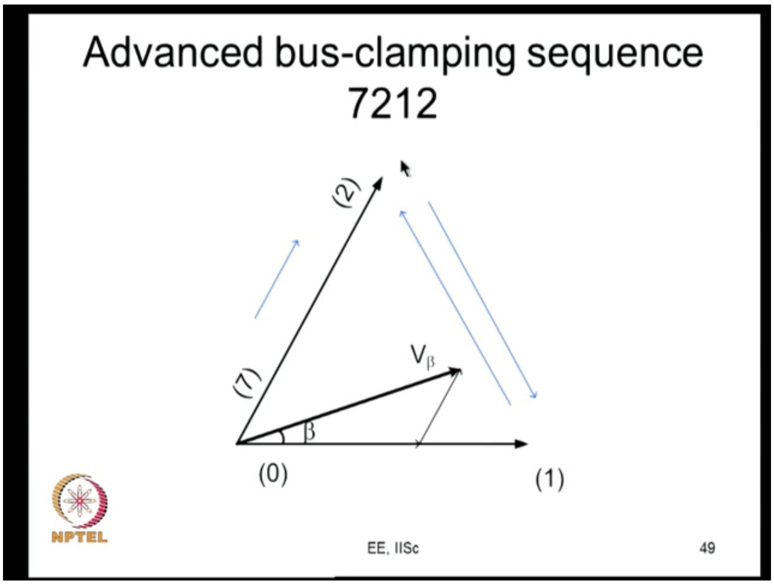

So, the same way 7212, you can start from 7, you can apply you can avoid the pivot state 0 you can apply this for the entire T z go over apply here for T 2 second T 2 by 2 here this stay for T 1 seconds go back and stay for T 2 by 2 seconds. Again 2127 is possible.

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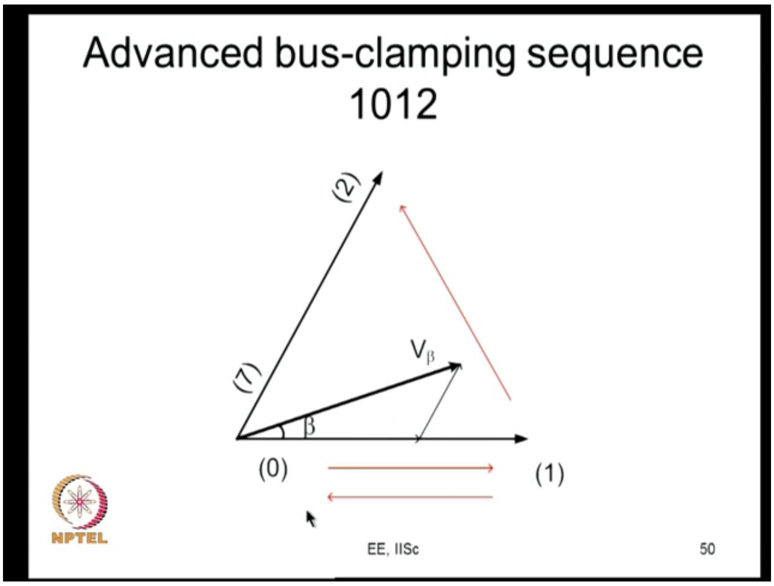

So, all these ideas that you have for two-level inverter can be extended. So, this is 1012.

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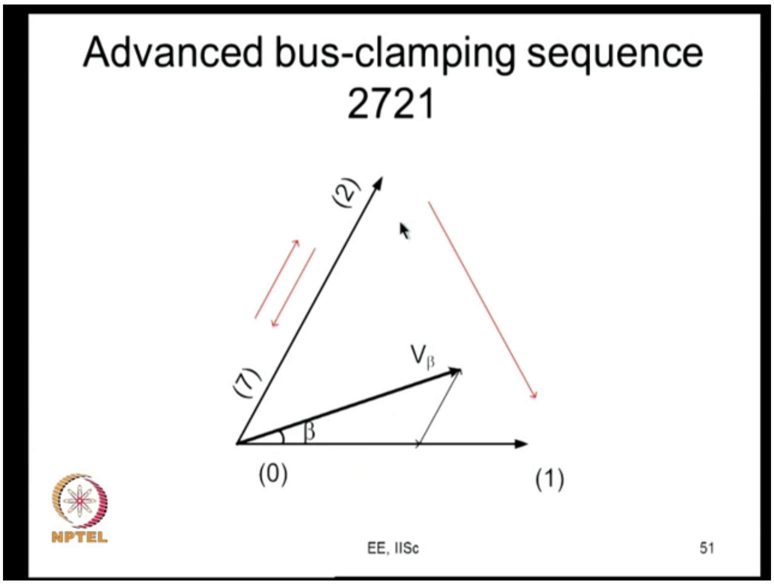

And this is also you have 2721. So, all the these bus-clamping sequence can now be extended. So, given a three-level inverter that reference vector you identify the nearest pivot vector and subtract that you get your reference vector corresponding to the conceptual two-level inverter. So, it is the conceptual two-level, you can used it as a two-level inverter. So, for this you know you can calculate your vector times T 1, T 2 and T z and like before we can use you know either of the two pivot states or you know we use only one and then we can also do this division of active state time, we can apply one of the active state twice. So, this is advanced bus-clamping PWM which is been extended for 2721 now.

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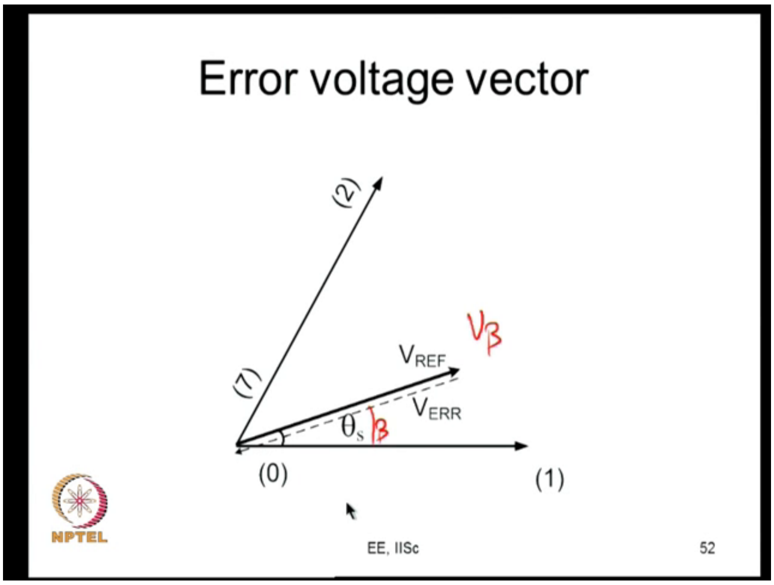

So, all this what will they do they will give you the same fundamental voltage, but the harmonics will change how to study that. One simple way is to look at the error vector like we did in the two-level case now. So, this is a reference that you want this is the V beta I was talking about actually. So, you can actually consider this as the V beta and the this angle as your beta. So, now this error is negative of that this now is when you have applied the pivot vector.

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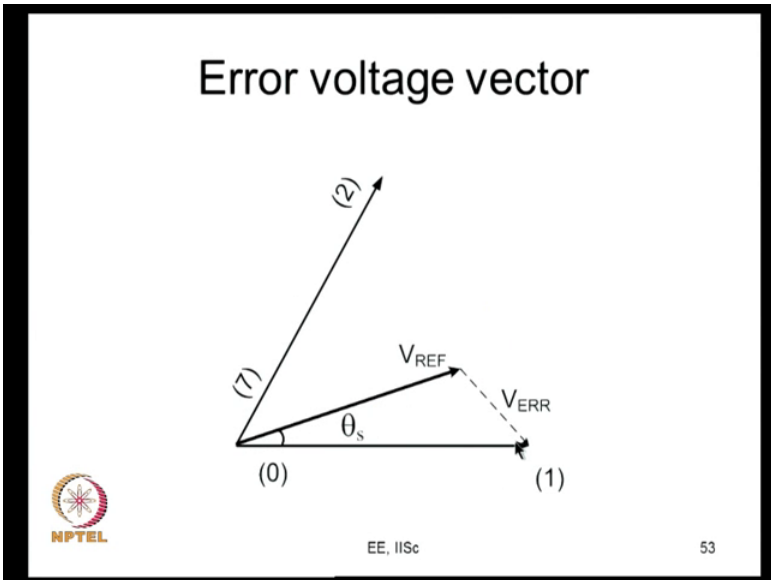

When you applied the active vector one, then this is the error voltage vector.

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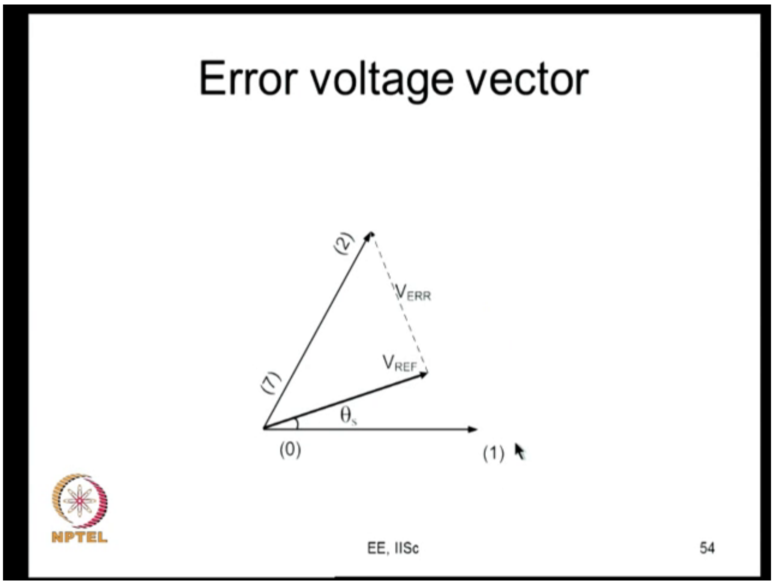

When you applied active vector two this is the error voltage vector. Now, what you need to do is you have to integrate this error voltage vector and that will give you the stator flux ripple vector, which is the measure of the current ripple. So, this is straight forward this is an extension of analysis that you really done for two-level inverter.

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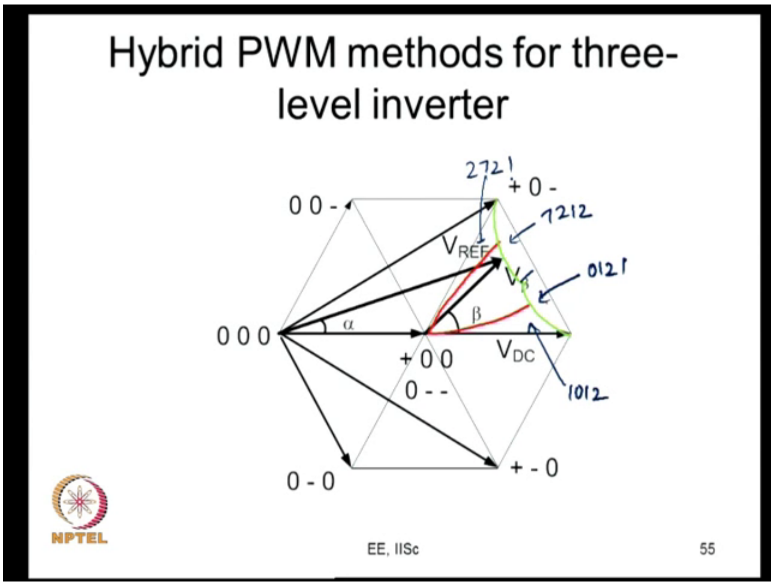

So, with this analysis it is possible for you to compare the different PWM methods I mean compare the different switching sequences. So, one thing which has actually been done this for example, such a study has been done and you have this thing extended here.

So, you have some the study has extended and it is shown that you have sequences for example, 0121 is better here and 7212 is better here and so on and so forth and here someone 012 and this is 2721. So, this kind of an analysis has been done and you also have hybrid PWM methods which are actually been developed.

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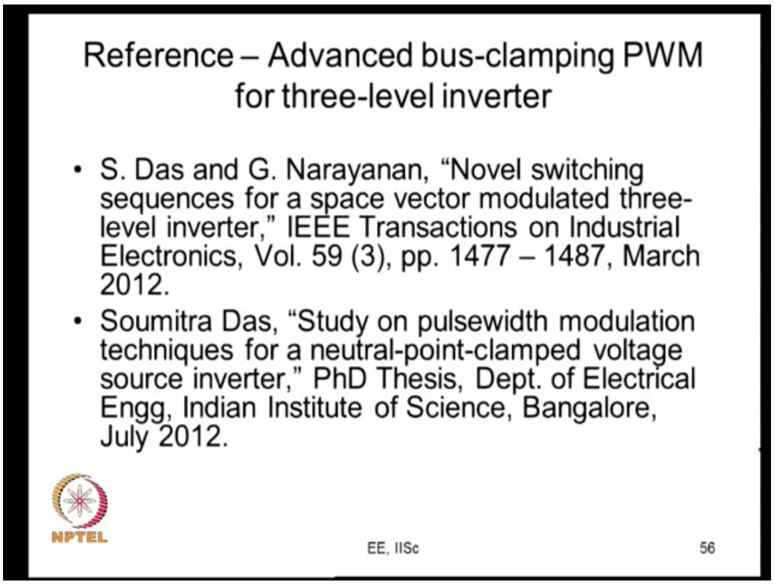

So, this many of these ideas are actually the novel switching sequences are discussed extensively in this paper this is a very recent one I triple E transactions on industrial electronics. And this thesis talks about these things in good detail on this advance bus-clamping PWM and how you would evolve hybrid PWM methods. So, this practically brings us to the most of the things that we really wanted to discuss here.

So, if you look at what are the various things that we really looked at. So, it is about power electronic converters. Why do we need power electronic converters that was our starting point. What is that is you may have your dc, you know you may have your load and you may have your supply. The supply and the load they may not have the same requirement, for example, the load might be requiring ac where as your supply might be requiring dc. So, in such kind situation, you require a power electronic converter now.

And many there are power electronic many most fundamental of the electronic converter we look at are dc-dc converters and we looked at primarily dc-ac converter which are actually extensions from those dc-dc converter now. So, you know we tried to look at this topologies from dc-dc converters. So, dc-dc converter if you look at a buck converter or boost converter essentially is has a single pole double pole switch, we use the same single pole double throw switch and we realised three phase inverters and you know we also looked at voltage source inverter and we looked at current source inverter. So, we basically reviewed the topologies in the basic ideas as far as the topologies are concerned are you know you are connecting switches. In power electronics what you have other than R, l and C, you have switches this is something that I have mentioned previous lecture I feel it worthwhile to you know read again. You connect it in such a fashion that you know normally you have single pole double throw single pole multiply throws switches and the poles always have the current stiff elements in the series, and the voltages have the you know the throws have the voltage stiff elements across them, so that is how you normally have.

In a voltage source converter, you have the voltage source available across the two throws; if it is a three-level inverter, you have three different throws and you have the voltage source available across that, and the pole is usually a load terminal now. So, this is what you really do and you come to this now. So, once you have a power electronic converter you have a basic dc to ac converter, it can be two-level or it can be three-level. One of your first thing that what you want to do is you want to control the fundamental voltage, you have your dc bus voltage 600 volts with 600 volt dc bus, it might be possible for you to realise a some ac voltage like whose peak line voltage is actually 600 volt. To that extent, it is possible for you to do that.

So, you want to control the fundamental voltage, so that is one of the primary purposes why we did this particular course now. You have voltage source inverter and we have voltage source inverters, we have current source inverter, this course we have focused on voltage source inverters. And why because they are more popular now. You have this device is like IGBTs and MOSFETs now and they come with anti parallel diodes and you know they can conduct in both directions while they can block voltage in only one polarity. And the earlier era we had thyristors and thyristors are very racket devices you know they can block voltages in both directions, but conduct in one direction. So, they were actually suited more for current source inverters.

So, current source inverter and thyristor they go better with one another now, but the more thyristor take too long to commuted and there have been many issues about commutation you need additional commutation circuit and so on and so forth now.

Whereas, you know now the modern devices are easy to turn on and turn off like IGBT it can also handle 1000 or 2000 volts 700 volts or so and handle 100 of amperes. So, you know it is good. So, you have a good current have capability and you have IGBT. So, therefore, you know we have been looking at voltage source inverter. And with this voltage source inverter, we have been looking at how to control the fundamental voltage what you have to bear in mind is there is no unique way of doing it, there are multiple ways of doing it now.

So, what we tried to explore is explore some multiple ways how exactly you can go about doing. And these multiple ways will give you the same fundamental voltage, but they will give you different harmonics and that would mean that RMS current is different and; that means, your losses are different that could mean your pulsating torque is different in applying in a motor drive. And the other important thing is this different PWM means methods could mean your power conversion efficiency could also be different. So, PWM has a very significant effect on the waveform quality and the power conversion efficiency. So, we have tried to look at the various aspects related to PWM and we analysis and we tried to design a few PWM method and so on so forth.

So, we focused and voltages inverter for the reasons I told you we looked at two-level and three-level inverter. We stopped beyond that because only two-level and three-level inverters are commonly used in the industry outside. So, you know I hope that you had useful outputs here and you know this is very closely related to the work that we do here at the Indian Institute of Science.

I would acknowledge all the members of power electronics group past and present at the Indian Institute of Science who have contributed to this work and it was the pleasure teaching this course year and I mean I have been there is a pleasure giving this 40-lectures. And I hope that you enjoyed this lectures and do let me have your feedback on this lectures whenever you have a chance to.

Thank you very much.