Pulsewidth Modulation for Power Electronic Converters
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Lecture – 38
PWM for three-level neutral-point-clamped inverter – 1

Welcome back to this lecture series on pulsewidth modulation for power electronic converters. So, incidentally today we are getting started off with the last module of this lecture series. This is a 40. This is a series of 40 lectures, and these 40 lecturers are organized into 13 modules. And today we are going to get started off with the last module which is on multilevel converter or PWM for multilevel converters.

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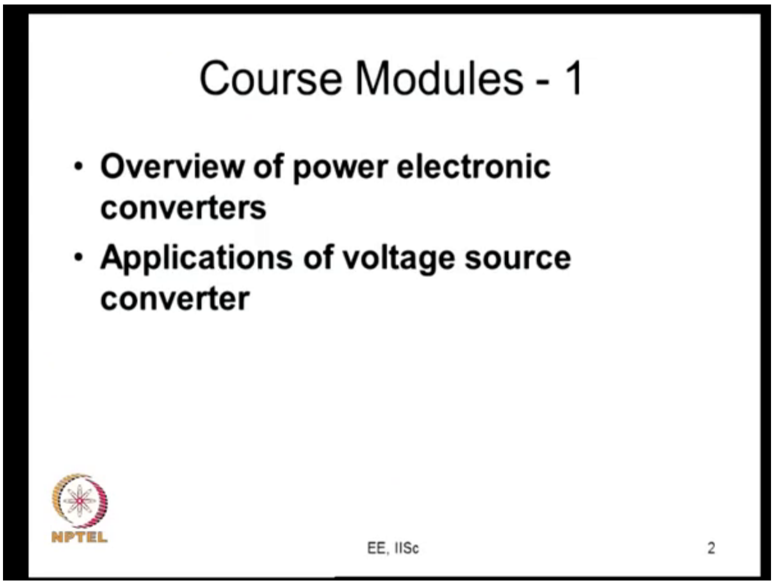

So, the different modules are organised like this. I am just trying to recap. So, that you can have a quick understanding what happened when, and you know if you have not followed all the previous lectures, you can go on catch up with the particular module and so on so forth.

So, what we started off with is actually overview of power electronic converters. In fact, we started off we know how to board connect switches, how not to connect switches that you know we have to make sure that an inductive circuit does not get opened out or a capacitance does not get started and so on so forth. So, we found that the DC DC converter its essentially, like it is a single pole double throw switch, and we looked at DC

DC converter, we looked at DC AC converter like voltage source inverters, and current source inverters, and we also looked at a multilevel inverter let say neutral point clamped inverter or flying capacitor inverter or so on and so forth. We discuss the power topologies the power converter topologies, how are the various switches connected, and why they are connecting the way they are, that was essentially what need to do this now.

So, for this multilevel converter if you are going to follow this, a fresh, you need to basically go away to this module, and look at some of this lectures which introduce a multilevel converter. Particularly a neutral point clamped converter or what is called as a diode clamped converter. So, you may have to look at that and then you have to restart. Of course, I will be picking up the threads from there and we will have some discussions on that also.

And the next module, the second module is actually on the applications of voltage source converter now. So, we have lot of voltage source converter DC AC conversion. You know we, like we have IGBTs we have MOSFETS and I G B TS, which are switches which are capable of conducting in both directions an IGBT with anti parallel diode can conduct in both directions and it can block voltage of own polarity; such switches are ideally suited for voltage source converters. And you use the voltage source inverter normally to drive motor drive, for variable speed, you knows speed drives; that is a very important application. You also use voltage source converter for active PWM, you know our active PWM rectification. You try to rectify you know at unity power factor, and the ensuring that the rectifier input currents are almost sinusoidal. We will have sinusoidal plus may be (Refer Time: 02:55).

So, the PWM rectification is another application of this, and we also have like, things like static compensation, and many grid connected applications are possible here. We are briefly reviewed the applications, and we also looked at you know what kind of load models etcetera could be used and so on so forth. Now so, these are actually, this is the first set of modules. These are more general power electronic course modules.

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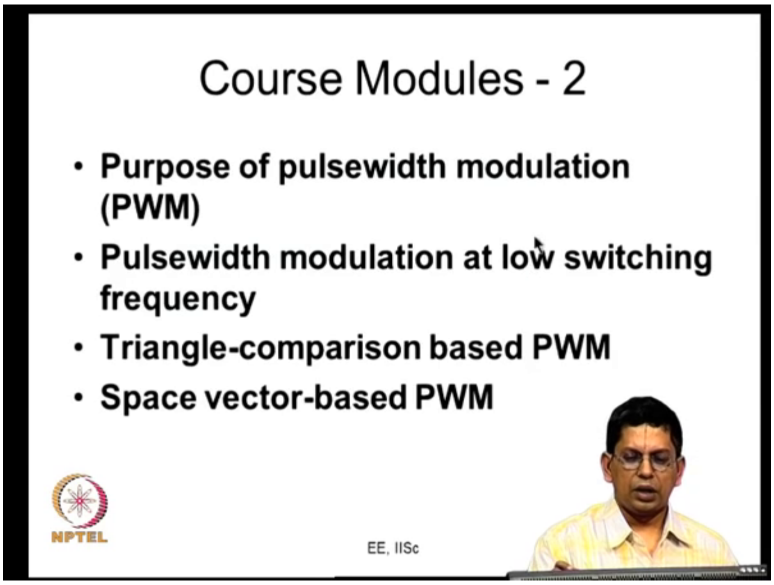

So, here we get particularly into PWM and some basics of PWM basics, PWM generation. So, in this we looked at Fourier series in how a form recomponents and symmetries, why symmetries, why half wave symmetry, why quarter wave symmetry, what happens and so, on, like in these two modules. For example, like half wave symmetry leading to absence of even harmonics and so on so forth. And in this module we particularly focussed on low switching frequency PWM, when you have many let us say two switching angles in a quarter cycle and three switching angles in a quarter cycle and so on. You now selective harmonic elimination is one way.

So, we looked at selective harmonic elimination. We also briefly discussed offline optimal PWM and. So, we tried doing this module, for one reason was like such low frequency PWM are applicable at high in, for high power drives, where the devices cannot switch at high frequency, because every time it turns on it turns off there will be huge amount of energy lose

So, device cannot go through several switching cycles, and then that is one reason. The other reason is more academic from the learning point of view. It is good to learn this well, and you know you can grasp several of the fundamentals here, and therefore, we go about doing it now. These low frequency PWM which we had done for two level inverter are certainly applicable to three level inverter; that is one reason I am talking about it now. And these ideas like what we said about half wave symmetry and quarter wave symmetry and things three phase symmetry and so on; that we discussed here, are all equally applicable here also.

In the case of two level inverter if you look at the pole voltage you may have only two levels like plus Vdc by 2 and minus Vdc by 2. Here your pole voltage will be more detailed it would have plus Vdc by 2 0 or minus Vdc by 2. Never the less the same principles are equally applicable. And you can generate low switching frequency, selective harmonic elimination for multilevel inverter there have been lot of work on this. Though I am not going to be specifically spending much time, I mean discussing this on that selective harmonic elimination for multilevel

So, whatever has been discussed for two level, the same principals could very well be extended to multilevel now. This is an important module, triangle comparison based PWM. So, particularly sinusoidal PWM, and then different kinds of common mode injection now. So, we would look at how to extend the sinusoidal PWM to this case of three level inverter.

So, that is one important topic that we will anyway take up for discussion. And once you do the sinusoidal PWM, it is also possible for you to add certain common mode and compare them with; that it is also possible. So, that is also something we can look at. So, the other thing that we need to do is, space vector based PWM. So, what we will do. First we need to understand the various voltage vectors produced by three level inverter there is a big difference here now. Earlier in a two level inverter you had a few switching states, there are three legs. In two level inverter also there are three legs, and three level inverter also there are three legs, because we are talking of DC to three phase AC conversion. The number of legs is same. In a two level inverter while there are only two complementary switches. In a three level inverter there are 4 switches; 2 pairs of complementary switches rather, and in a three level inverter your pole voltage can be plus Vdc by 2 0 or minus Vdc by 2. In a three level inverter if you look at the voltage space vectors an inverter can produce that will be many more than what can be produced by two level inverter. In a two level inverter there are 8 inverter states 2 multiplied by 2 multiplied by 2. Here there are 27 inverter states 3 multiplied by 3 multiplied by 3

So; that means, are many voltage space vector. So, today we would look we would see what are the various voltage space vector produced also, and we will try and see like this triangle comparison PWM, when you consider sine triangle PWM for example, and one interesting thing is its not unique, when you extend sine triangle PWM from two level to three level, it is not unique. There are several ways of extending which actually can lead to different PWM methods, which have whose waveforms might have different harmonic properties.

So, we would like to see the see switching sequence for some of them. So, we would look at in terms of the inverter voltage vectors. Most probably in the next lecture, we would look at this space vector based PWM for three level inverters in greater detail. So, this second set of course, modules, which actually dealt with PWM generation. This is all for two level inverter. Once we understand what is the three level inverter and once we understand this it is possible for us to extend many of these to three level inverters.

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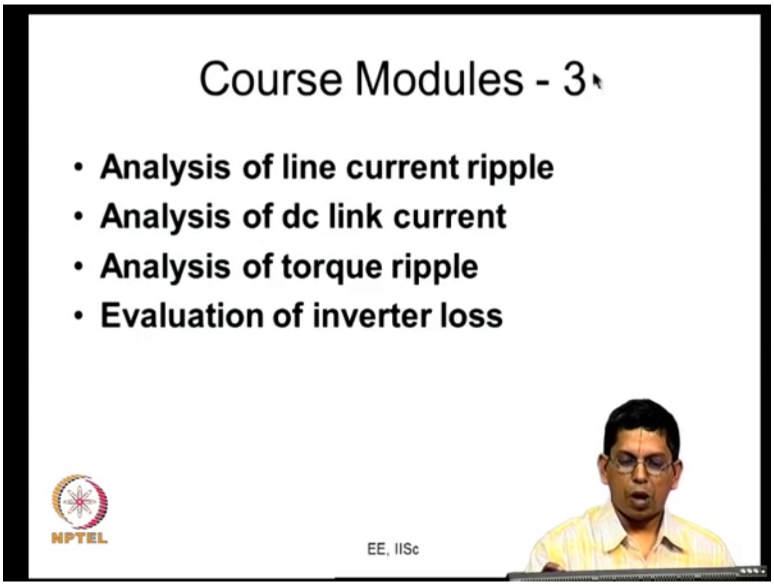

So, then the third set of modules where more about the analysis, analytical part in inverter now. Here the focus is not really on the fundamental voltage. The earlier case we learnt how to modulate the inverter, so that we get the desired fundamental voltage, here we are kind of evaluating. There are different PWM method, if there is a particular PWM method particular load how do I calculate the R m S current ripple. There are two different PWM methods, how do I compare the R m S current ripple, the burden of the discussion where actually you know that that is what those of focus of the discussions.

Of course, many of them were not in such detail as could be done in a regular classroom, but I tried providing enough inputs and also give references.

So, that you know it would be possible for you to do things yourself, and I am hoping that in the assignment sets and all that, you know they will also those homework problems might also be of some help to you, to understand this concepts better. The third set of modules is more analytical, we will look at how much is the current ripple for example, in the AC side, and we look at what is the DC link current; that is flowing on the DC side of the inverter, and this is closely related to the capacitor, because the DC component of the DC link current comes from the DC supply say the rectifier, and the ripple component of the DC link current, most of it flows through the DC capacitor, and that determines the R m S current in capacitor, that determines the power loss in the capacitor, that determines the heating in the capacitor and the life of the capacitor, and therefore, the DC link current is something very important from the capacitor point of view. So, we tried having a detailed discussion on the DC link current also.

Of course, these are all short modules, everything with 2 or 3 lectures each of these modules, but I am trying to give a certain amount of fundamentals principles, which are needed for carrying out this analysis. And one other thing is specifically in the context of motor drive is pulsating torque. These are all the effects of harmonics. The harmonics cause harmonic currents, and therefore, current ripple the harmonics also cause harmonics fluxes, and fundamental flux and harmonic current, and again the fundamental current and harmonic flux interact to produce pulsating torque

So, we discuss this pulsating torque for a single, I mean for low switching frequency case and also for the high switching frequency case. So, for the low switching frequency case we tried to evaluate fifth seventh harmonic voltages etcetera, we tried to look at the sixth harmonic torque. Torque for example, how you could evaluate specific harmonic torques like 6 12 etcetera, and we also looked at the possibility of eliminating say something like sixth harmonic torque or twelfth harmonic torque, by appropriately selecting the switching angle. And in the high frequency case where you know, we tried look at it as the integral of error voltage. We considered the error voltage vector and we tried to integrate that to get the state of flux ripple vector, and we use that q axis component of that to do this job here alright

So, what we are going to do, is the evaluation of the inverter loss is the next important thing from a practical point of view, which is what also something that we did now. And this inverter loss is interestingly that know, the basic ideas of conduction loss and switching loss etcetera, would actually apply two or three level inverter also. So, what we will see is, in two level inverter if you are looking at conduction loss, there are only two transistors. I mean two with antiparallel diodes. So, for a particular direction of current, it is only this one transistor other diode, they conduct alternately, and whereas,. So, there is always one device conducting in a leg at any point of time whereas, you find that in a three level inverter you will find that two devices are conducting at any point of time.

So, that the last to that extent conduction losses going to be more. On the others hand this switching loss you know whenever an inverter switches, if the inverter is a two level inverter, this switch is going to be switching a voltage of V d c. Whereas, as we will see here it will be switching only a voltage of Vdc by 2, and therefore, the switching energy loss could actually be lower. So, there are some reason where when you go to fairly higher switching frequencies, a three level inverter might lead to lower switching loss than the you know two level inverter, or the overall power conversion loss can also be lower than what you can actually get with the two level inverter.

So, sometimes for power quality decants applications, you could consider doing this, and there are actually comparative studies are also available. I would try to indicate some of these references to you, maybe in the next lecture or the last next two lecturers on this particular topic now.

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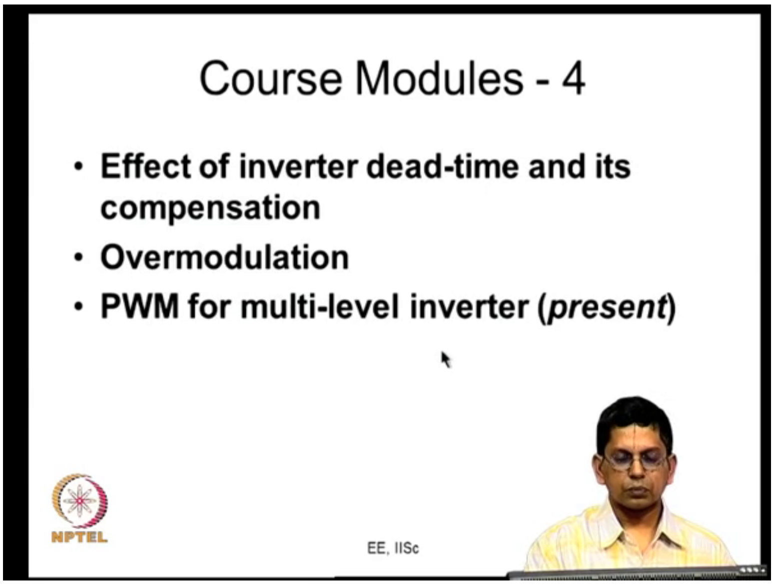

So, we also, this in the fourth set of modules we tried to look at the inverter dead time and what effect it happens now. Here also you have the same inverter dead time is required. There in in a two level case we had two complementary devices. So, you need a dead time between the two outgoing device is switched off first, and the incoming device is switched on later. So, there is a time delay of T D introduced between that. Here in a three level inverter you have two pairs of complementary devices, and you know again in the outgoing device should be switched off first and then the incoming device is later now, with certain amount of thing you can actually do this dead time analysis for here also, but that is something that we are not going to really look at.

Again we go in for this (Refer Time: 12:34) for overmodulation. This overmodulation you know what we achieve is, from sine triangle PWM when we go to common mode injection; we are able to increase the voltage by 15 percent. We can again increase like from 0.5 VDC or some 78.5 percent of 6 step voltage, we come to 90.7 percent using carry common mode injection al1 from 90.7 to 100 percent of the 6 step voltage, we will need overmodulation; that is something that we discussed in the last module.

The same philosophy can actually be used with certain modifications two or three level inverter also, but in three level inverter you know if two level inverter with overmodulation, you can increase it from 90.7 percent to 100 percent, nearly 10 percent increase in the voltage is possible through our modulation. Whereas, that percentage increase could actually be little lower with this, and you know of course, there in those algorithms that I have mentioned, can be explained, some of them have been extended, and some can be extended to overmodulation of three level inverter

So, if necessary we can also do that, so, but we would be focussing on this is present modules on PWM for multilevel inverter. So, we will take a look at a multilevel inverter, and we will look at the pole voltages, the inverter states and the voltage vectors, that are being produced by a multilevel inverter. Then we will look at sinusoidal PWM for two level, and how do extend sinusoidal PWM from two level to three level inverter, and we look at some 2 3 interesting possibilities, and will make a comparison of them. And then we will go into space vector based PWM for multilevel inverter, and possibly look at a some advanced bus clamping PWM this.

So, like we had the PWM methods, we had the continuous P W methods, we had the discontinuous or bus clamping PWM methods. For two level we also can have them for the multilevel inverter. So, such things have also been researched. Just like we have the advanced bus clamping PWM methods for the two level inverter, it is possible for us to have a advance bus clamping methods for three level inverter also. There have been 1 or 2 recent publications in that regard. I would also give an indication to you in that particular direction ok.

So, now we move on to our you now this lecture number 38, which is on PWM for three level neutral point clamped inverter, this is the first lecture. So, we will have three such lectures like this. So, I call this PWM for three level neutral point clamped inverter one alright.

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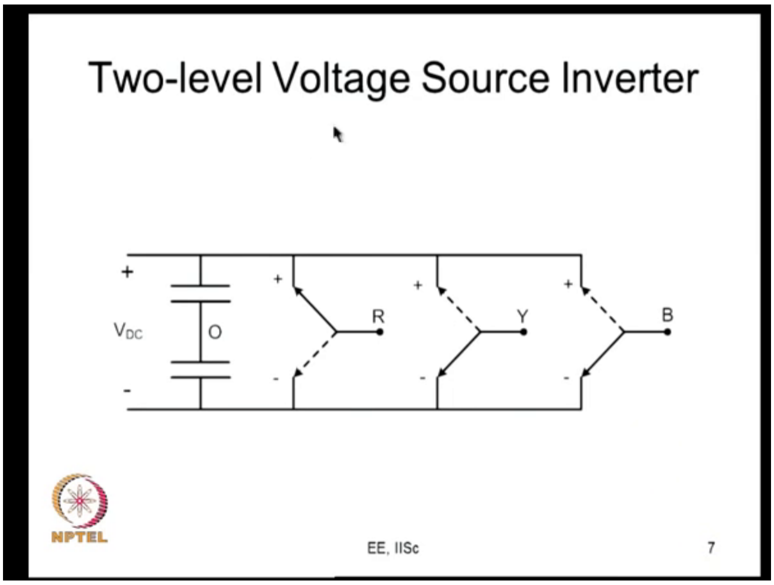

So, now we have this two level voltage source inverter. And as I said before this thing is a single pole double throw it is a voltage source inverter this source is a DC voltage, and it is a inverter it is expected to produce AC voltage here low. The loads are expected to be inductive and therefore, you find that the pole is connected, every leg is a single pole double throw switch, and the pole is connected to one of the load terminals, because it makes sure that the inductive currents do not get, you know opened, you know that there is always a path for the inductive current to flow through. And the DC side is a stiff voltage source, you have a voltage source here and there is capacitance to supply this additional ripple component and so on.

So, this is voltage stiff, and the voltage stiff component is coming across the two throws. So, there is no possibility of getting shorted. So, the inductive load does not have possibility of getting opened out, and this does not have a possibility of getting shorted; that is why the poles as you might recall are connected in series of the inductive loads, and the throws are connected across voltage, stiff elements such as voltage source or capacitors now. So, this is a single pole double throw switch, and again another single pole double throw switch for the Y phase leg, and single phase double throw switch for the B phase leg.

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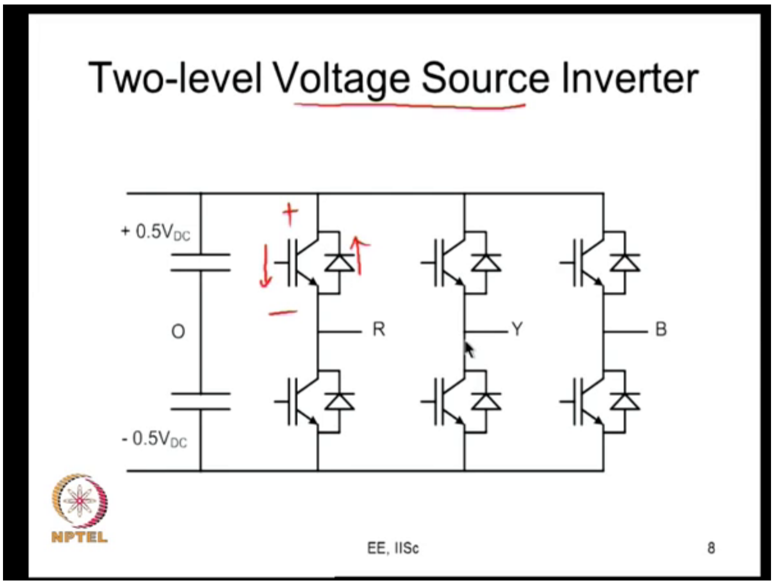

So, we realise this using a device which can conduct in both directions, but can block with only one polarity, where this is positive with respect to this, you want me to write can do this now this is something which we have already done; whereas, the conduction can be in both directions.

So, we have such devices and such devices are used in voltage source inverter. If you going to the current source inverter, you will need the complementary, I mean you will need the dual of this. A current source inverter would require a switch, which can block voltages of two polarities, but maybe conduct current in only one direction alright. So, this is a voltage source inverter, and it is realise using a single pole double throw switch as I have shown here alright.

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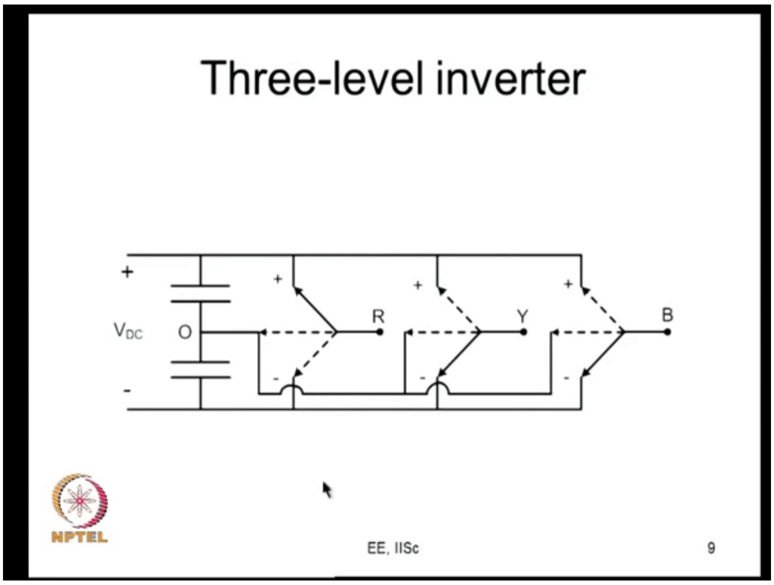

Now, we need a multilevel converter, what we do is, single pole double throw there is no. There is a pole, why there is this pole there is a load terminal is connected here, and you used a single pole double throw so that you had an capable you know you could apply either plus this VDC by 2, measured with respect to O, or minus VDC by 2 measure with respect to O at R. So, your waveform quality can be improved, if you can also connect R to the midpoint o; that is one of the ideas now.

So, you have an option of either connecting it to the positive bus, or this DC midpoint or negative bus. Earlier the DC midpoint in a two level inverter is not available for making an electrical connection. So, here it is available for making an electrical connection, and. In fact, sometimes load current may flow into or out of this particular point. So, you have single pole triple throw switch, and that is what we call as a three level inverter. Of course, you can consider single pole 4 throw switch and that could be called as a four level inverter. Again single pole 5 throw switch that can be called as a five level inverter. Again you have to be a little careful when you talk about three level, here we say three levels, because the pole voltage can have three different levels plus VDC by 2 0 or minus VDC by 2.

So, there are some authors, who would count the number of levels let us say in R and Y. If you look at R and Y you will have five different levels, because it can be plus VDC or it can be plus VDC by 2 or it can be 0, or it can be minus VDC by 2 between the 2, or it can be minus V d c. So, there are five different levels. So, sometime you may find the same thing getting referred as five level inverter, but our convention is quite clear. We say the number of levels, we related to the number of pole voltages. You look at the pole voltage and the possible number of levels of pole voltages in the two level inverter there are only two of them impossible plus VDC by 2 minus VDC by 2. Here it is plus VDC by 2 0 and minus VDC by 2. Hence we call it three level inverter

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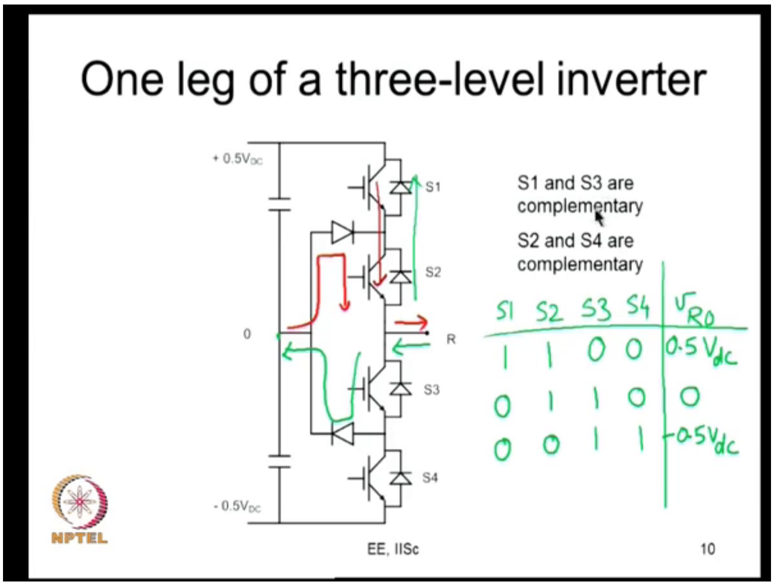

So, we realise this three level inverter, we discussed this one of the lectures where we spent extensively on how to derive this, and this is what is a single pole triple throw switch realization that we finally, came up with. So, if the top two devices are on S 1 and S 2 are on, the bottom two will be off S 3 and S 4 will be off and in that case R will be connected 2 0.5 V d c. So, this is the pole getting connected to the top throw. The pole getting connected to the bottom throw is again straight forward to c. What you need to do is, keep this two off, and keep this two on S 3 and S 4 on. Therefore, what you will get you will have this pole getting connected to the bottom throw. So, v RO will be now equal to minus 0.5 Vdc earlier it was 0.5 V d c.

Now, it is also possible for you to connect R to O. What do you do? You turn off S 1, again you turn off S 4, you turn on a S 2 and S 3. So, R could establish a connection with O, and through which part, there are two different parts that would depend on the load current. For example, if the load current is in one direction, the load current could potentially flow like this, or if the load current is in the opposite direction it can actually flow like this. Let me draw that for your convenience. If the load current is in this direction for clarity let me draw, in this direction, then the load current can actually flow like this, from the. On the other hand if the load current is in the opposite direction, the load current could flow like this I wanted to draw it in green. So, let me erase that.

Now, let me draw that in green. So, if the load current is in the opposite direction, because it is an AC load you know. So, current can be in both the directions, then you will see that conducts like this. This would be the direction of path. So, which transistor which diode would conduct would actually depend upon the direction of current, but you need keep both of them on now. So, there are three. So, in this case what will happen R gets connected to O, and a you have your v R is equal to Vdc by 2.

So, this O is sometimes called the neutral DC neutral, and hence the name neutral point clamped inverter, because you have an ability to apply this there. And you are using this diodes which are called clamping diodes and. So, the since diodes are being use for clamp connecting this midpoint to this midpoint, sometimes they are also called diode clamped inverter. So, these are all the alternate names that you will use now. Sometime there are also cases where instead of this diodes active switches are also used. In that case somebody may call it as active clamped, you know three level inverter, but that is something that we are not looking at now. So, this is called neutral point clamped inverter or three level you know diode clamped inverter or three level inverter, these are the different names now. So, if you can see this way, we have a capability of this, that is a voltage source, and this is the pole and there are three different throw voltages, and this converter has an ability to apply the pole, I mean the throw voltage, any desired throw voltage at the pole, irrespective of the direction of current; that is the attribute of voltage source converters.

Let say the current is like this. Now you want this voltage to be applied, you turn on this two. So, your current conduction will be like this, through the transistors and it will go along like this now. If the current conduction is in the opposite direction then it would go like this and go back there. So, it is possible for you to conduct like this, maybe I can draw that. So, for example, the conduction can be like this. In the other direction, the current conduction could be like this.

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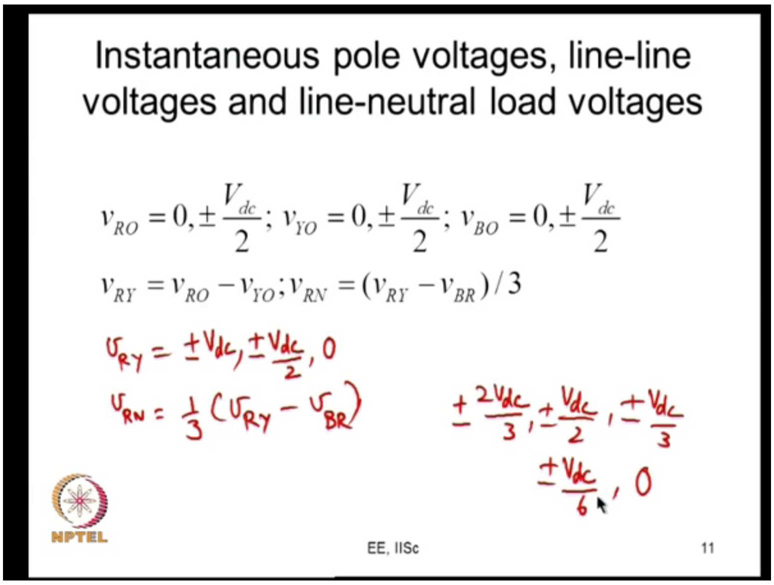

So, this converter has an ability to apply either 0.5 Vdc or 0, or minus 0.5 Vdc at the pole, regardless of the direction of the current at the pole. It can apply any of the throw voltages at the pole now. The same way it is bottom thing also now.

So, let us just summarise the whole operation in terms of a table. So, you have S 1, you have S 2, you have S 3, you have S 4 and you have the pole voltage v R O. So, now, if S 1 is on and S 2 is also on, S 3 and S 4 are off you get 0.5 V d c, you get 0.5 V d c, this is the voltage now. Again if you have S 1 as off, S 4 is also off S 2 and S 3 are on, then you get v RO is equal to 0. So, that is getting connected to that. So, you know, this is where the, you know pole voltage, pole is getting connected to DC bus midpoint. Again you have another possibility, you have a S 1 and S 2 are off, and S 3 and S 4 are on. In this case you are applying minus 0. 5 Vdc at the pole, mentioned with respect to this point O.

So, you have these possibilities now. So, you do not consider one of those possibilities. What is that possibility? Keeping S 2 and S 3 off, S 2 and S 3 off and S 1 and S 4 on, because; that means, S 2 and S 3 are off means it is totally open, the load is open, which is not something that you want to do. So, you have this kind of possibility here. So, what can you identify here? You look at S 1, and whatever is your S 1, S 3 is complimentary to that if S 1 is high S 3 is low, if S 1 is low S 3 is high. The same way you can say S 2 and you can say S 4, they are also complimentary with one another. Therefore, you can say that S 1 and S 3 are complementary and S 2 and S 4 are complementary. This was the reason I told you that you know in a two level inverter you have one pair of complementary switches, here you have two pairs of complementary switches now.

So, there it is suffice for you to generate one gating signal, and the other gating signal would come by taking its compliment. Here you have to generate two gating signals, may be for S 1 and S 2 and S 3 would come by complimenting S 1 and S 4 would come by complementing S 2. So, you need to produce to gating signals, and that is going to significantly change. So, earlier in sine triangle PWM for two level inverter, you could compare 1 sine wave with 1 triangle. Now you cannot have 1 sine wave with 1 triangle, because you have to produce to two signal.

So, it has to be like 1 sine wave with 2 2 carriers which is what we look at, and sometimes it can also be with 2 sine waves with 1 career. So, this is something that we will look at here. So, S 1 and S 2 and. So, now you need this kind of a logic. So, we need to generate S 1 and S 2 for example, and S 3 and S 4 can be generated as complements of S 1 and S 2 respectively. So, if you look at the instantaneous pole voltages, just we have been discussing it can be 0. When would it be 0? So, when both, you know like when the pole R is connected to O, by the middle two switches being on then v RO is equal to 0. The same way v Y can being 0, if the middle two switches on the Y phase leg are on. Again if the middle two switches on the B phase are on and the extreme two are off, you get v BO is equal to 0.

So, this is something different from the two level inverter, and the plus or minus Vdc by 2 is similar to what you had in a two level inverter. Except that you have to keep both S 1 and S 2 on and S 3 and S 4 off for plus Vdc by 2. For this minus Vdc by 2 you must have S 3 and S 4 both on. So, there will be two switches will be conducting, it could be 2 transistors or the 2 antiparallel diodes that could be conducting, when you are really doing this now. The instantaneous pole voltages are 0 plus or minus Vdc by 2 0 plus or minus Vdc by 2 and so on. So, when I write Vdc by 2 you can inherently see, the time ignoring the device drops just as we have been doing all through ok.

Now, v RY is what is v R Y, the same kind of equation as before v RO minus v Y O, and what is v R N one third of v RY minus v B R, assuming the load to be star connected balance load, the neutral is not connected anywhere else. This is the kind of star connected balance load you assume here as before. So, the main difference that comes is in this value 0. Otherwise it is similar to that of a two level inverter. So, the analysis procedure from pole voltage you go into line to line and the line to neutral voltage on the load, they are pretty similar now.

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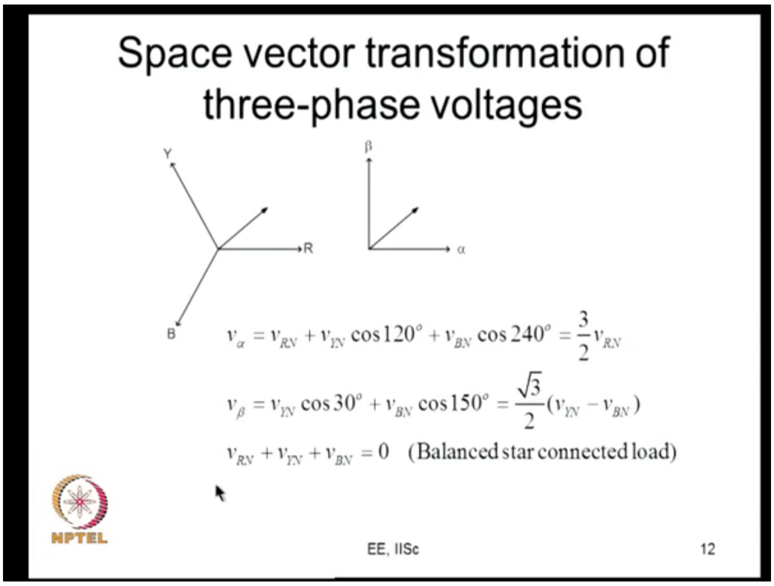

So, now we have v R O, v Y O, v BO and they can, from that you can get v R Y, v Y B and v B R and you can also get v R N v Y N and v B N. And v R N v Y N and v B N can be used top 10 V alpha V beta, the same space vector transformation is valid.

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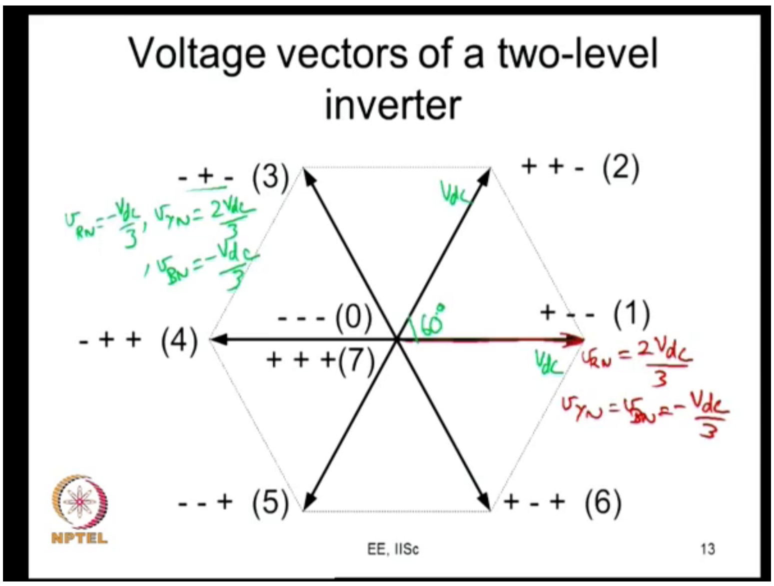

Because v R N plus v Y N plus v B N is equal to 0, under this condition you have V alpha is equal to 3 by 2 v R N as before, and V beta is equal to root 3 by 2 times v Y N minus v B N. The only difference would be in the possible values of v R N. Earlier in a two level inverter what are the various values of v R N possible. The various values of v R N possible would be 0 plus or minus Vdc by 3 plus or minus 2 Vdc by 3. Whereas more number of values would be possible here. For example, you may be able to look at plus or minus Vdc by 6, and the so on so forth. So, you will have more number of values, because v RO you have one additional value. So, v RY you will have more additional. So, you have three possible values against 2, in case of two level inverter. So, v RY you would have five different values, it can be plus Vdc by 2. Let me just write it down here

So, v RY would be able to take values like plus V d c, and it will also be able to take minus Vdc right, because you now if v RO is minus Vdc by 2 v Y O is equal to plus Vdc by 2. And v RY can also take the values of plus or minus Vdc by 2, and it can also take the values of 0. So, there are five levels. This is why I said that sometimes authors may call this is a five level inverter because v RY have 5 possible values now. Again next if you trying to do v R N is equal to 1 by three times of v RY minus v B R. So, you have different possibilities, if you substitute one after the other would be able to get many different possibilities. So, what are the different possibilities. So, v RY itself has 5 possibilities, v B R itself has 5 possibilities

So, let us look at some possibility, if let us say v RY is equal to plus Vdc and v B R is equal to minus V d c, in that case what you will have is you will have 2 Vdc by 3. This is similar to what we had in a two level inverter. So, let me write down one possible value, is 2 Vdc by 3 as in the case of two level inverter. Again it can be plus or minus. If v RY can be minus Vdc and v B R can be plus V d c. So, you can have plus or minus Vdc by 3 as had in a two level inverter. Now let me say v RY is equal to plus V d c. whereas, v RY is equal to minus Vdc by 2. So, in that case what you will have, this is Vdc and this is minus of minus Vdc by 2 will be 3 Vdc by 2. So, that will be I a only equal to Vdc by 2. I hope I am not making any mistake this is Vdc and minus of minus Vdc by 2 is 3 Vdc by 2. So, you have Vdc by 2 as your v R N

So, its also possible that you can get Vdc by 2 as a possible value, and it can be plus or minus Vdc by 2. So, you can also look at plus or minus Vdc by 3. So, you would also be able to look at plus or minus Vdc by 6, and you will also be able to get 0. So, if you look at this interestingly, what you will get here is, if you need 2 Vdc by 3; that is possible with only one possibility; that is v RY has to be Vdc and v B R has to be minus V d c; otherwise this is not possible 2 Vdc by 3 is not possible, but if you look at Vdc by 2, then you can look at possibility of this being plus V d c, and this being minus Vdc by 2 or you can also look at the possibility of this being Vdc by 2, and this being minus V d c.

So, you have multiple possibilities that lead to here now. And if you look at the possibility of Vdc by 3 you will see that there are more number of possibilities, which will give you Vdc by 3, and even more number of possibilities are Vdc by 6, and finally, for 0 you have may, you know more possibilities in the sense in both can be Vdc that is one possibility both can be Vdc by 2 that is another possibility second, and both can be 0 that is third possibility, both can be minus Vdc by 2; that would be the fourth possibility both can be minus V d c, that would be fifth possibility you have 5 different possibilities.

So, the highest possible line to line voltage that is a unique possibility, and when you go to slightly lower you know line to line voltage you have more possibility. As we go to lower and lower voltages you get more and more possibilities, and 0 is where you have the highest possibility, and this is a three level inverter. You go to 5 level inverter 7 level inverter you have many such possible state on many many possible states which will give the same voltage and these you now that is what is interesting.

So, there are two different inverter states which can possibly give you the same line voltage, and multiple inverter states can give in the you that; that is what gives us the leave way to design more and more PWM methods as for as the load is considered, it is going to look at what is the voltage. So, if it is 0 the load does not care, if this 0 has been achieved by keeping all the three poles at plus Vdc by 2 or minus Vdc by 2 or all three poles at 0. Again we with you know if v RY may be plus Vdc by 6 it can be, you now v R may be at some level Y phase can be at some level B phase can be some level, but v RY can be plus Vdc by 6, and v Y B can be minus Vdc by 6 and v B R can be 0 for example.

So, there are many many possibilities; that is the multiple inverter states lead to the same set of three phase output voltages, you we need particular output voltage; that is what the load cares, but that is possible to generate using multiple sets of inverter sates. Particularly when you are talking of voltages which are low in a amplitude. So, not close to V d c. So, this is what allows us to design many many PWM methods now. So, now, if you have v R N available, you can also do this. So, v R N and you have v Y N and v B N values, they can be transformed into space vector domain 3 by 2 times v R N is your V alpha and a v Y N minus v B N into root 3 by 2 is V beta.

So, as you know what we did this, this is the R Y and B axis and this is the three phase axis, and these are the two phase orthogonal axis in the stationary reference frame alpha beta. We call them alpha and beta and again there are different arguments and different conventions. You basically have a V alpha as V n cos 0 plus v Y N cos 120 plus v B N cos 240 and that becomes 3 by 2 times v R N when you have this condition v R N plus v Y N plus v B N is equal to 0. And then you have this V beta, V beta as a essentially v R N sine 0, which is 0, and v Y N sine 120, which is same as v Y N cos 30 plus v B N sine 240 which is same as v B N cos 150, and this becomes root 3 by 2 times v Y N minus v B N

So, once we have v R N v Y N and v B N its possible to calculate V alpha and V beta, and these are the components of a vector. So, you can say V alpha square plus V beta square and root, that will give the magnitude of vector tan inverse of V beta and V alpha will give the angle of the vector now. So, its possible for you to calculate many of the inverter states. This is what did for two level case also. In a two level case they are very very clear. All the top switches are on is plus plus plus. So, here you will see all the three line to line voltages are 0, all the three line to neutral voltage is v R N v Y N and v B N are also 0, and you will get your V alpha to be 0 V beta equal to 0. The same story when you use minus minus minus that is all the three bottom are off. Whereas, if you use plus minus minus like here, you will see the that you would have got excuse me

So, if you use for example, plus minus minus, you will see that your v R N is 2 Vdc by 3. This is a two level inverter and v Y N equals v B N equals minus Vdc by 3, and this v R N v Y N and v B N will give you V alpha is equal to Vdc and V beta is equal to 0 and that is what is this vector, that is what is this vector. Now let us say I am looking at this inverter state, here v RO is minus Vdc by 2 v Y O is plus Vdc by 2 and v BO is equal to minus Vdc by 2. On the other hand if I look at v R N, I will find that v R N is minus Vdc by 3 v Y N is 2 Vdc by 3, and v B N is equal to minus Vdc by 3. So, 3 will sum up to 0 v RO plus v Y O plus v BO will not sum up to 0.

Whereas, v R N plus v Y N plus v B N will be sum up to zeros. So, this is what you will have. So, minus minus minus you add all this and be you get this. So, this is 1 vector. So, this will actually give you V alpha is equal to minus 0.5 V d c, and V beta is equal to root 3 by 2 Vdc you get this now. You can do similar analysis for all these and you get this active vectors. You will always find that they have a magnitude equal to, the active vectors will have magnitude equal to Vdc this is according to our conventions the way we have defined V alpha and V beta here, you go by that we get magnitude V d c, this is also magnitude Vdc and this angle is 60 degree.

So, this is what we did in a two level inverter. So, the same transformation, but different sets of three phase pole voltages, that is all that matters now. The different three pole voltages will give you two different sets of line to line voltages, and different sets of line to neutral voltages, and therefore, different sets of voltage vectors.

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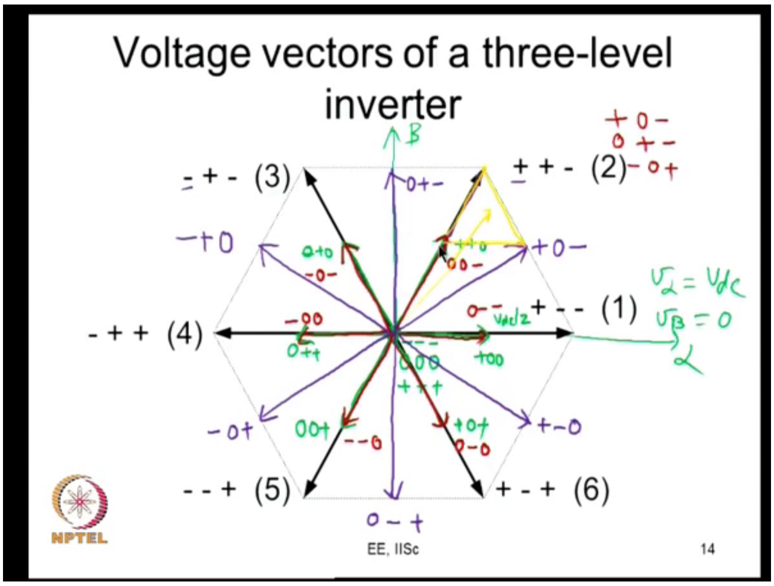

In a three level inverter this is what we are going to see now. So, three level inverter you have a particular cases. So, like for example, you take the first case that is R phases top, is connected to the top throw that is top two switches, are on Y phase the bottom two switches are on, the B phase also bottom two switches are on. So, here you have v RO is equal to plus Vdc by 2 v Y O is equal to minus Vdc by 2 and v BO is equal to minus Vdc by 2. This is same as what you had in a two level inverter. So, the inverter states, we call as plus minus minus and the vector is same thing it will be V d c. So, this is your V alpha axis and this is your V beta axis. May be it may be good for me to indicate our alpha axis and beta axis this is what is our alpha axis, and this is our beta axis

So, you have the same thing of your V alpha is equal to V d c, and V beta is equal to 0 for this case. So, you have this vector as we have drawn here now. Again all this states that I have shown here are common to two level inverter and the three level inverter. This means R phase top two devices are on Y phase top two devices are on, d phase, bottom two are on, and the pole voltages are plus Vdc by 2 plus Vdc by 2 minus Vdc by 2, we just possible for a two level inverter also in case of two level inverter also, and the vectors is same angle is the as the magnitude as V d c, and angle is 60 degrees here. Again this minus plus minus is something which is common, because you now we this is again what you have the two level inverter. So, again 4 5 and 6 these are similar to what we had in a two level inverter.

So, there are how many inverter states are there now. There are 3 possibilities. For example, R phase may be positive plus Vdc by 2 or it may be connected to the DC midpoint 0, or it can be connected to the negative bus minus. So, there are 3 possibilities; Y phases 3 possibilities, B phases 3 possibilities it is 3 multiplied by 3 multiplied by 3 there are 27 states. Out of 27 states we have accounted for only 6 states. Now if you look at for other states for example, let us say we have a state minus minus minus.

So, what does it mean, in all the 3 legs the bottom devices two devices are on. So; that means, the line to line voltages are 0, the line to neutral voltages on the load are zero; therefore, V alpha V beta are 0 I am showing it by a circle. I mean this is the null vector. This same situation is obtained even when you do 0 0 0. All the three phase poles are connected to the DC midpoint. The middle two switches are kept on in all this cases now. Again you connected as plus plus plus that is the top two switches are on in both the in all three legs now

So, all of them will lead to this now. So, now, you see a small difference. Earlier it was only minus minus minus and plus plus plus are available in two level inverter, and these were called the 0 states, which we called 0 and 7 we designated them 0 and 7 minus minus minus and plus plus plus, here all bottom devices are on, here all the top devices are on. So, here we have all the bottom two devices are on all the top two devices are on and all the middle to devices are on.

So, you have these 3 0 states now. So, we have accounted for 6 plus 3 9. There are still 18 more states are remaining now. So, what are those states now? See for example; let us say here it is all connected between plus and minus. All these states, though you can connect it to 0 in these 6 states you find that the inverter leg is connected either to positive or to negative, and not all of them positive not all of them negative; that is what you find

So, let us say we look at only those combinations, where the inverter leg is either connected to positive or to zero that is again possible you now. So, in that case what happens is the inverter, the three level inverter reduces to something like a two level inverter whose DC bus voltage is Vdc by 2 alright. So, let me just write that down now. So, I am looking at plus 0 0. So, what happens with plus 0 0, I am going to get an inverter staright like this plus 0 0. This magnitude will be Vdc by 2, why, because is very similar to the case of three level inverter, I mean the two level inverter, except that the DC voltage now is Vdc by 2. So, the line to line voltage here are, minus Vdc 0 I mean Vdc 0 and minus V d c, here it is Vdc by 2 0 and minus Vdc by 2 that is R. So, you will have half of this now. Again you can use that, again in a that is you look at combination where they are connected only between plus and 0.

So, you get the other combination. So, if we have plus plus 0. Here you may have minus plus 0 that will lead to a vector like this. Again you will have not main, I am sorry it did I say yeah this is 0 plus 0, and here I have 0 plus plus, and here I can think of 0 0 plus, and here I can think of this state plus 0 plus. So, these are 6 inverter states, where the legs are connected, the midpoints are connected either to first plus or 0. So, these are like similar to active states in a two level inverter, but who is DC bus voltage is Vdc by 2 and. So, all this produce you know voltage vectors of length equal to Vdc by 2, and their angles are 60 degrees as before. Now if you have plus 0 0, what is R phases Vdc by 2, Y phases 0 B phases also 0 the pole voltages is 0 you can the. What is the line to line voltage. It is plus Vdc by 2 v RY is plus Vdc by 2 v Y B is 0 v B R is minus Vdc by 2 you can achieve this same thing if for example, we use 0 minus minus

So, here again v RY will be plus Vdc by 2 v RY will be 0 v B R will be minus Vdc by 2. So, they will result in a same set of three phase line to line voltages, and therefore, this three phase line to neutral voltages on the load. Again therefore, the same voltage vector, again I can look at this same, I can look at 0 0 minus this leads to the same set of pole voltages, this also leads to same vector. Again I would have the inverter state minus 0 minus leading to the same vector. I will have minus 0 0 here I can have minus minus 0, here I can think of 0 minus 0. So, these are another 6 more vectors.

So, these are combinations, the where I have done in the red ink, these are all combinations of 0 and minus,, it is like I am having a three level inverter, but I am switching only between minus and 0. So, some legs may be connected to 0, some other the remaining legs will be connected to minus. So, these would be active vectors. So, now, how many have you been able to account for, we have been able to account for first this 6 outer vectors and then this 3 9 and then now twelve of them. So, about 21 of them we have accounted for. Now how many inverter states are remaining, 6 inverter states are remaining. What are the inverter states remaining. The kind of inverter states remaining are of this nature; like plus 0 minus, this is what we have not considered till now, or something like 0 plus minus, or minus 0 plus and so on.

So, what do these things stand for the actually one of them has plus Vdc by 2, another one would have minus Vdc by 2, and third one would have 0 that those you have 6 combinations will be available. So, if you take the first two phase, it can be either plus Vdc by 2 0 or minus Vdc by 2. So, the second phase can have two possibilities and third will have 1 possibility. So, you have 6 such states now. So, the question is, where will be the vectors now. So, if you look at plus 0 minus v RY is equal to Vdc by 2, and sorry v Y B is equal to minus Vdc by 2 v B R is equal to minus V d c. So, this is Vdc by 2 Vdc by 2 this is minus V d c. From here you can calculate v R N v Y N v B N V alpha V beta and you can count to that.

So, there is no issues, you can actually do it, but what you will find here it is, you see here plus minus minus and you see here plus plus minus and when you go for plus 0 minus these will actually will be midway between the 2. It will be symmetric from this, and what you will find here is that, actually it will go like here. This would be the vector produced by plus 0 minus. Again this will be the vector produced by, here in the transition from plus to minus if you look at 0 plus minus. Again here if you look at this this will be minus 0 plus, and that would produce a vector like this, and I miss something here. So, it will be minus plus 0 and that would be producing a vector like this. Then if you look at here, this will be 0 minus plus, like this now. And then you look at here is the other fellow will be producing here this is plus minus 0.

So, you can see some interesting observations here. Now there is this 0 state, how many active vectors are here, actually 27 inverter states are there. These 6 states leads to 6 vectors, they lead to 6 vectors are all of magnitude Vdc by 2. Then there are twelve different inverter states, which lead to 6 distinct active vectors of Vdc by 2. So, two of them produce the same vector. Now then you have three of them producing the same vector the null vectors, there are 3 0 states they produce that, and then there are this 6 active vectors which produce I mean active states producing 6 active vector.

So, whatever tip is found on the outer hexagon, they correspond to twelve different inverter states, and they produce twelve active vectors, and that is what you find them then, and the inner one there are twelve of them producing 6 active vectors totally, and the innermost are three inverter states producing a single active vector. So, if you count the number of distinct active voltage vectors or voltage vectors, you have 12 plus 6 plus 1 there are 19 distinct voltage vectors produced by 27 inverter states, you see that there are lots of possibilities.

In the case of two level inverter you had only one possibility, this vector can be applied either using this state or that state, and that itself lead to many PWM methods. So, that is the main reason why you had the bus clamping PWM method, the common mode addition is mainly, because of this. And we further invented that you know like look that, I mean learn that the active state can be applied more than once and so on or active state to can be applied more than once and that lead us to the advance bus clamping PWM method.

Now, if you look at there are so many possibilities, this can be applied through three different inverter states, and all these vectors can actually applied by 2 using two different inverter states. So, a three level inverter gives you much more degrees of freedom you know much, you know lot more opportunities to explore and design new PWM methods than even a two level inverter does, and we are to be the two level inverter we could discuss the PWM methods for about 20 25 lectures, you can see that you know we can discuss about PWM methods probably for 50 lectures, but that is not what we are going to do, because the fundamental principles are many a times common.

Once you understand the fundamental principles for PWM for two level inverter, and then you understand what is the three level inverter, then you should be able to design reasonably good PWM methods for a three level inverter, and therefore, will be restricting it only to three lectures here alright. So, but you should realize that it gives lot of exciting possibilities there are so many so many possibilities of doing things now ok

Now, let me just give a another more indication, you will need a vector you know for example,. So, let me say, let me take this triangle, it is better that I choose yet another colour, would this be alright. So, let us say, you have this triangular region. I have a tip falling here, you have a reference vector falls here. So, now, what happens is, I can use the three nearest vectors, this is what we are actually heading towards. Why does it give you better way from quality, if you need to reduce you know produce this vector using a two level inverter, you have to use this null vector, you have this active vector use this active vector; obviously, you will be using active vector 2 for the longest duration I have followed the vector 1 and then the null vector produce this one

So, whenever you are applying you are never getting to apply this, you are applying here here and here, and error is very high. Particular when you are applying active vector 1 the error between the desired vector and the actual vector is. So, long again when you are applying null vector that is. So, long now you since you have many more possibilities what you can do. You apply the three closest vectors. So, you see that the error is so small here also error is so small. So, this error voltage vectors is nothing, but the harmonics you now you have the ripple voltages in all the three phases.

If you transform the ripple in all the three phase into the space vector domain, that becomes your error vector again this error vector, that gives your instantaneous error vector now your instantaneous error vector is low and therefore, its integral the instantaneous state of flex ripple are the instantaneous current ripple is going to be low, and that is the reason why three level inverter gives, you know main reason gives a better way from quality than that one now. Again you see that there are multiple possibilities. For example, there are two different inverter states which you can use to apply this, and that will give you lot of opportunities to design PWM methods now.

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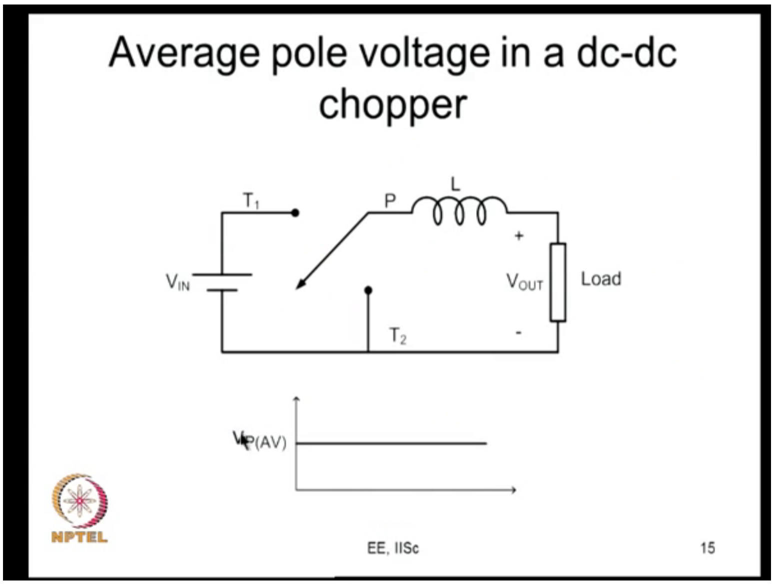

So, if you look at now we have looked at just the switches. We have looked at the possibilities of pole voltages and so on. Now we would look at the average voltages, if you are looking at DC DC chopper, what you are trying to see is, you want you apply certain average voltage here; you would want that same average voltage applied at the pole now.

This is pole average pole voltage, at the poles sometimes it is V in sometimes 0, what you do is, you get certain average voltage. This average voltage will be constant against time, because that is what you want in a DC DC chopper. So, this switches you will make sure that their normally power flows in one direction, if this is the regenerative more load like a DC machine, you could actually make this switches conduct in both directions, and you can make this the regenerative choppers. So, you can make it a two quadrant chopper also.

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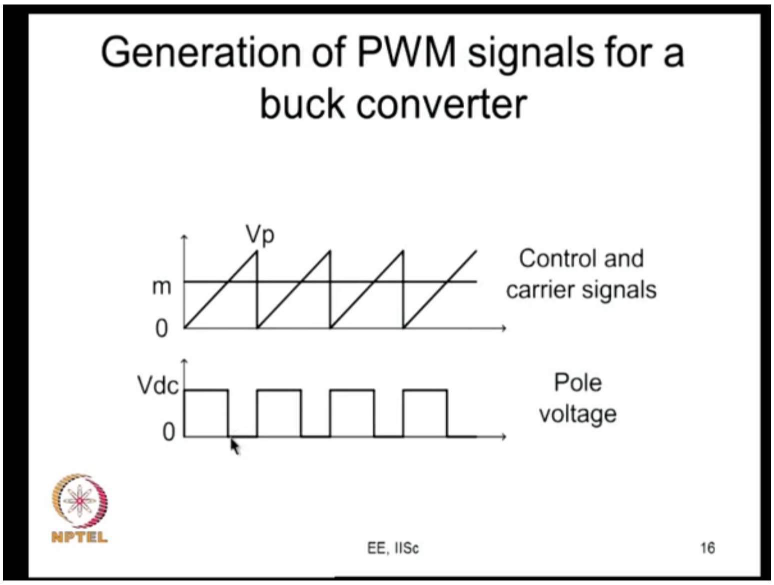

Now, what do you do, how do you produce the PWM signals is by comparing this career with a modulating signal, as we did before, and the mod the duty ratios are constant now.

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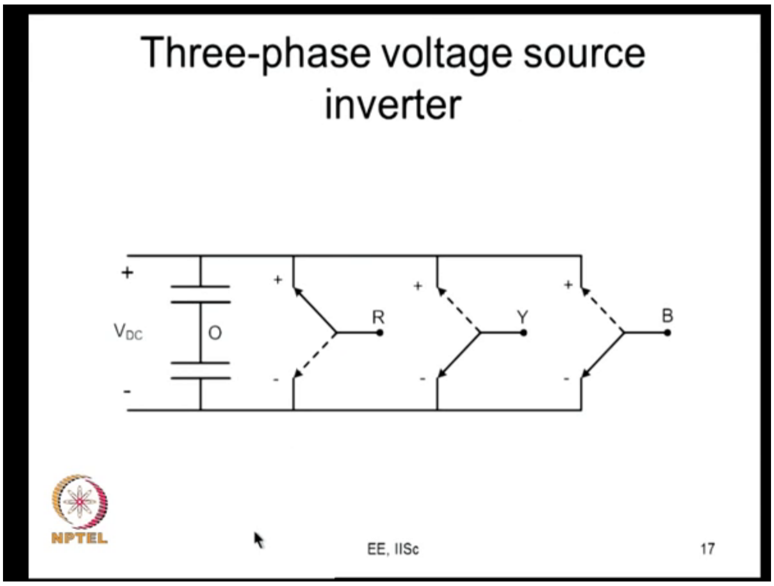

What we need in case of three phase inverter is, we would need this v RO average this pole voltage, the average pole voltage now needs to be varied sinusoidally. You want to vary v RO average sinusoidally, v Y O average sinusoidally, and v BO average sinusoidally; such that we will get v RO average as a sinusoid, v Y B as a sinusoid, and v B R as a sinusoid, and all this three sinusoids will be balance symmetric.

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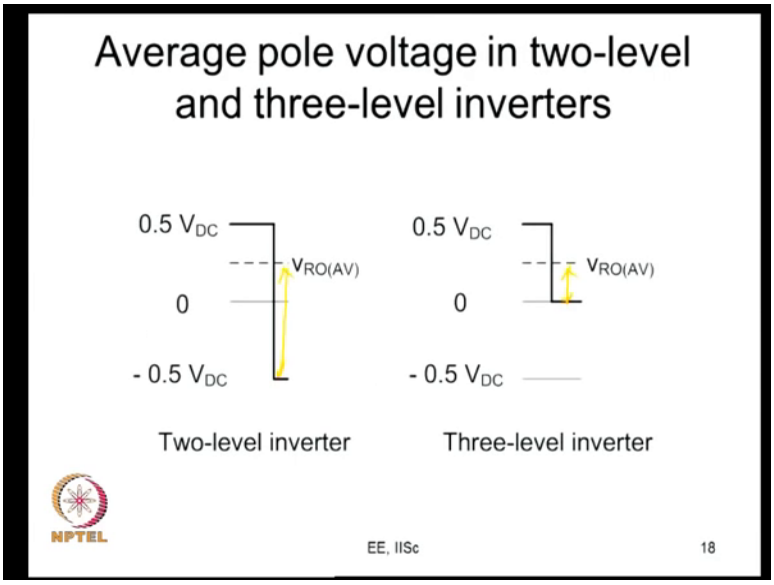

So, if you want to produce v RO average, if you lose two level inverter, you know we want this alternating. So, sometimes it will be positive sometimes it will be negative. If you want your v RO average something like 0. 2 5 V d c, in a two level inverter you could do this by connecting it to 0.5 Vdc for most of the time and minus 0.5 Vdc for a shorter duration of time. Whereas, if you want to do it with three level inverter, you do not have to use minus 0.5 Vdc at all and this is for 0.5 Vdc and 0. So, you will get that; 50 percent of the time you apply 0.5 V d c; 50 percent you apply 0 you will get 0.2 5 Vdc

So, what happens? So, you are able to generate the same average voltage, but the instantaneous error is small. Here the instantaneous error as, I have pointed out even in the lectures on multilevel inverter so high whereas, here the instantaneous error is so small. So, the worst case instantaneous error reduced and; obviously, be flux being is going to be reduced now. It is this reduction in the error voltage error in pole voltage is what got reflected as, the reduction in the voltage error vector, in the space vector domain alright. So, you can use like this.

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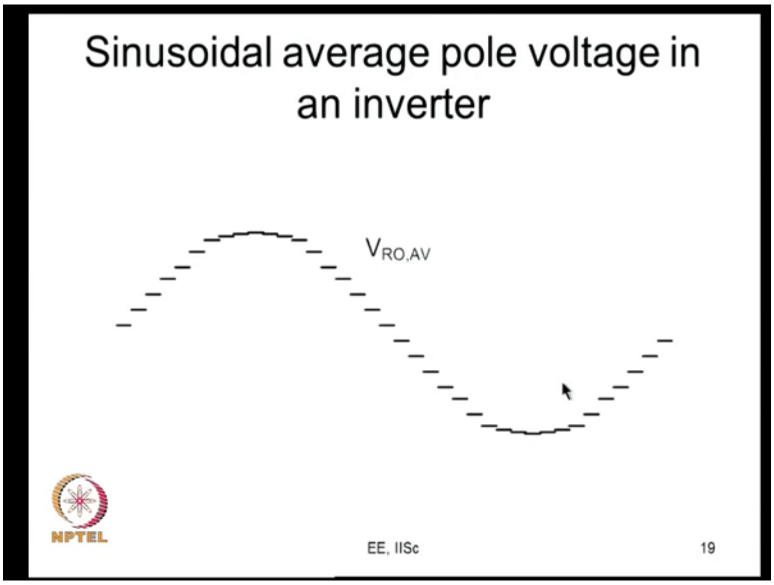

So, what we want to do is. We actually want to vary this it is we are v RO average sinusoidally, and v Y O average to be another sinusoid, at the same amplitude same frequency 120 degree later, and v Y O average also as another sinusoid.

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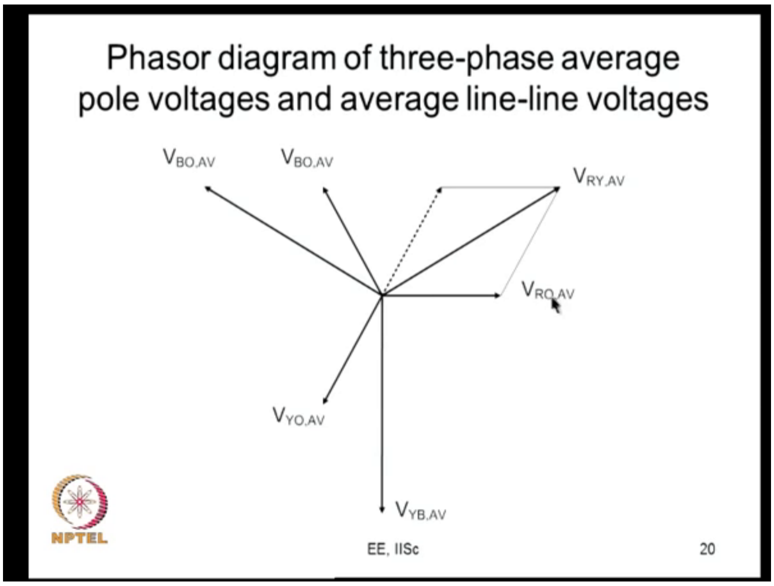

So, if we do this like that v RO average are all sinusoids, they are all same amplitude same frequency 120 degree phase shifted, then you will get your v Y R Y average like this, and v Y B average like this, and this I am sorry is v B R average. So, this is v B R average. So, you will you will get the three phase line to line voltages like that.

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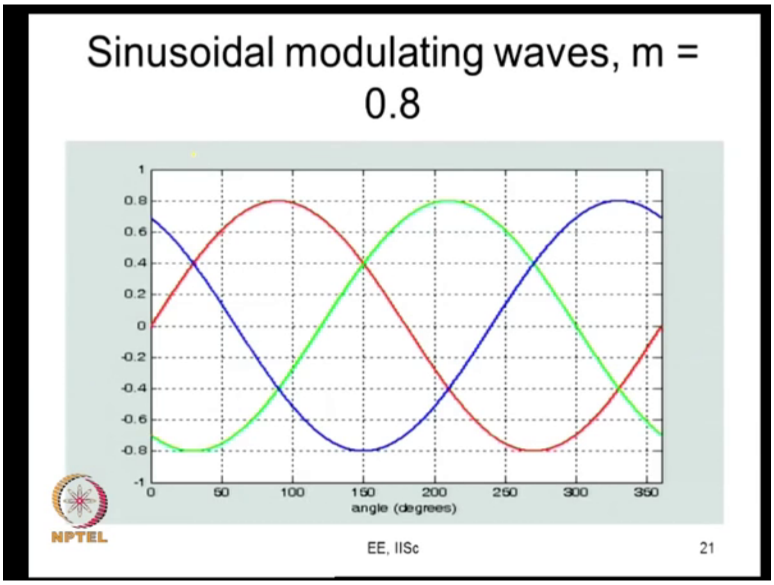

So, this same idea that we used in a sinusoidal PWM, we can use here for two level inverter. You can use three phase sinusoidal signals. The only trouble is they you cannot have single carrier as, we will just soon see now.

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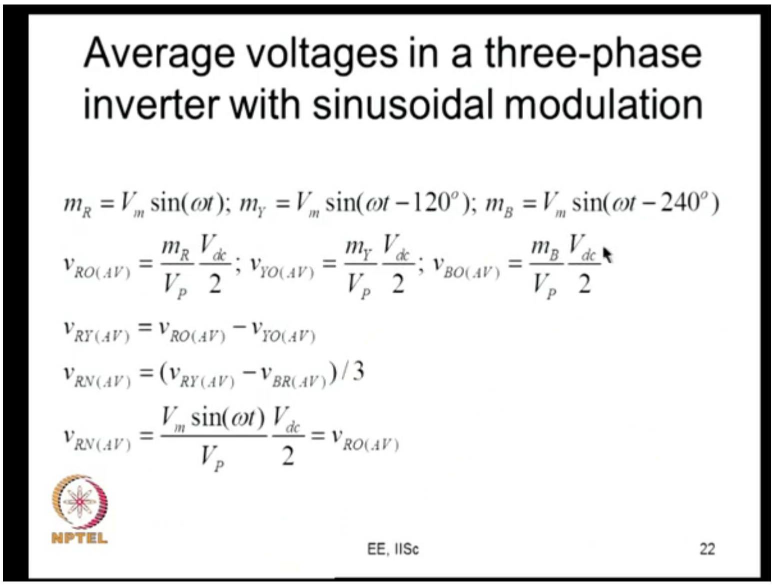

So, they are like m R m Y m b, and v RO averages m R by V p times Vdc by 2. So, you know we are not going to overmodulation. So, m R and v RO are just have the same wave shape, just scaled versions v RY average, v R N average and you know we know all this we have done this enough number of times before.

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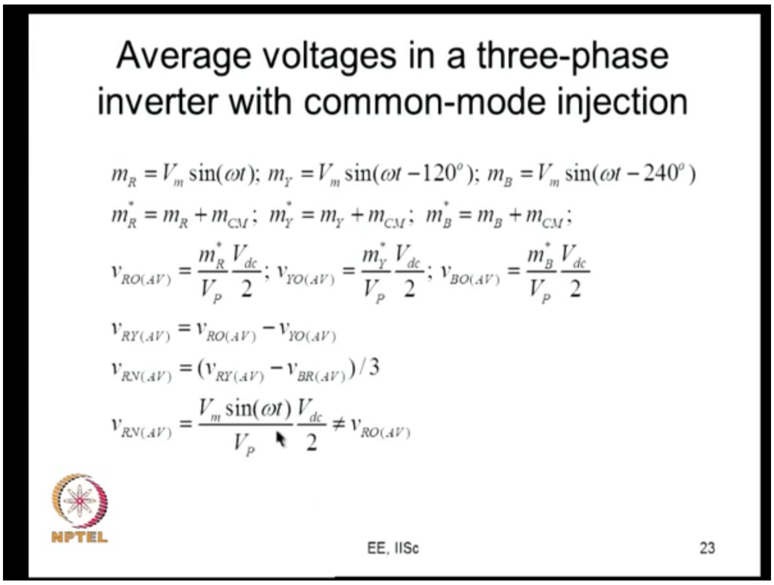

So, you can achieve what you want. You can also add common mode like we did in two level inverter; nothing stops us by from adding the m c m to m m R m Y m B to get your m R star m Y star m B star, and you tried to produce v RO average which is a scaled version of m R star, you produce v Y O averages which is scaled version of m Y star how you do it that is what we have to see. You need to compare them with triangle what kind of triangle we have to see now, but you can its possible for you to produce. Once you produce like this you have your v RO averages v RO average minus v Y O average, and v R N average just like this same as what it was in a two level inverter, and you know all this are very similar now

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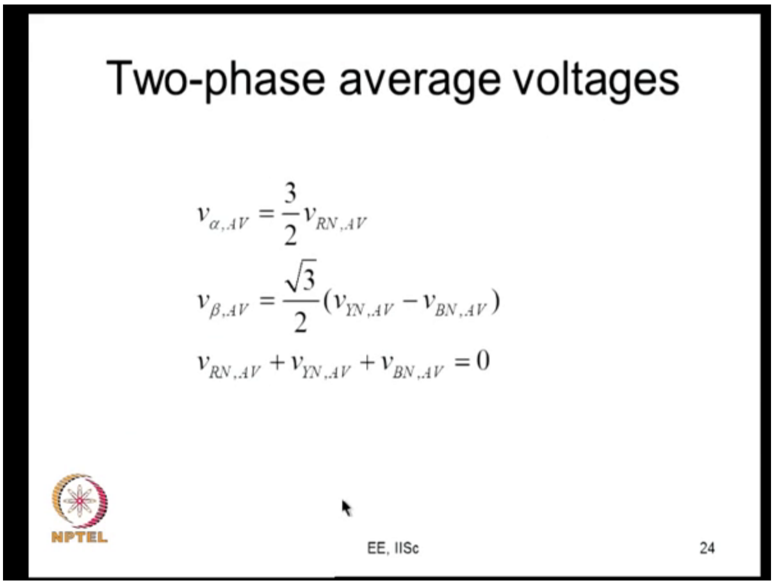

So, once you have v R N average v Y N average and v B N average, you can always transform them into V alpha average and V beta average, our standard space vector transformation. Of course, here the v R N average plus v Y N average plus v B N average is equal to 0 still valid now.

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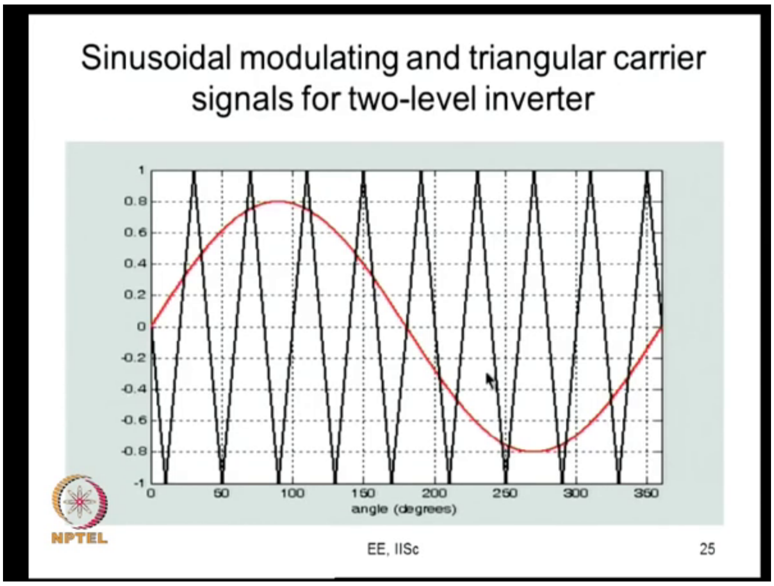

So, in that case different comes in the triangle for a example in in in the case of two level inverter, there is one modulating signal and one triangle, and there are other modulating signals Y B as well compared against the same triangle now, but the single triangle carrier will not suffice for you.

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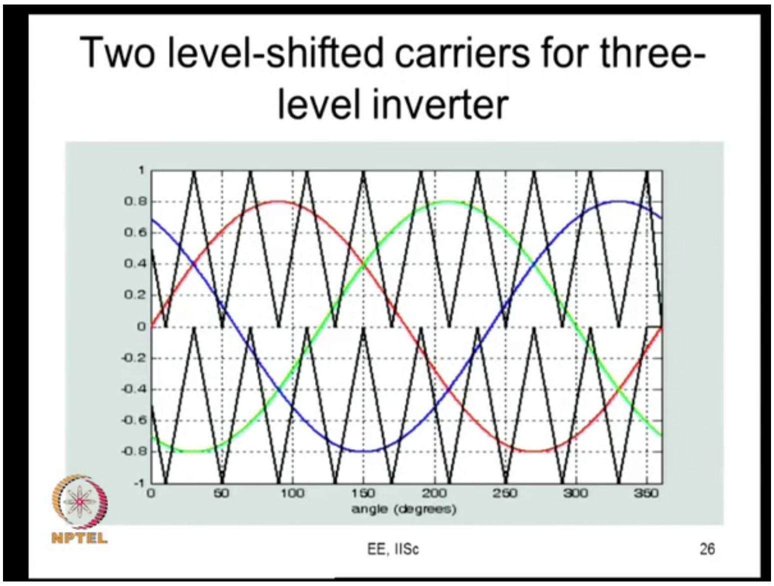

So, what you do now, is basically you have two different carrier is, one way of doing it is you have the same R Y b, but no have level shifter carriers

So, you see that it goes between 0 and 1 and this goes between minus 1 and 0s. So, you have two level shifted carriers. Now and this comparison can give you some switching, and this comparison can give you give you some other switching now. For example, your logic would be you take R phase here it is greater than both the carriers, then you can say R phase both the top devices will be on

Now, here you let us say take some other guess, you will take the R phase here. Now R phase is lower than this carrier, but higher than this carrier. So, you can see in for R phase, the middle two switches will be on. And now you take R phase here it is lower than both the carriers, here you can say that both the bottom devices will be on. So, this could be the switching logic by which you can come up and produce PWM wave forms. So, this can be done using two level shifted carriers. This is one good way of extending sine triangle PWM for two level to three level, and you know it actually the harmonic distortion is also pretty good with this as we will see, compared to other things now

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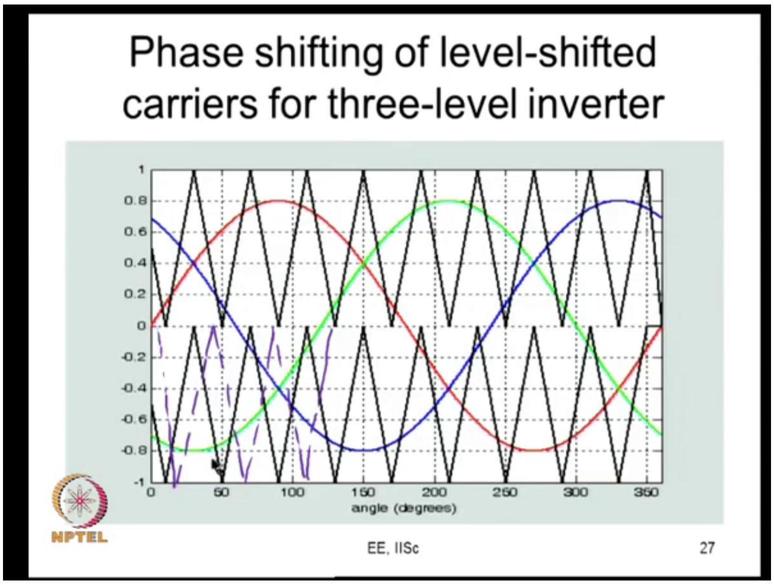

So, as just mentioned that you know you compare them with carrier and you know; obviously, these are high frequency carriers, and let me use a different colour here yeah. So, these are high frequency carriers, though I have shown the carrier to be of low frequency for purpose of illustration. What I can also do is. I can also have this phase shifted like this. I can also have the carrier phase shifted no problem. It will still work, the fundamental voltage I will still get

So, one of the two carrier are phase shifted from each other. So, what would be the effect of doing this now? So, you see that this is at some phase; this is at some other phase, maybe phase shifted by 20 degree or 30 degree at the carrier frequency. This will not affect the fundamental, but this will impact the harmonics. So, sometimes harmonics may change for better, or many times it may change for worse.

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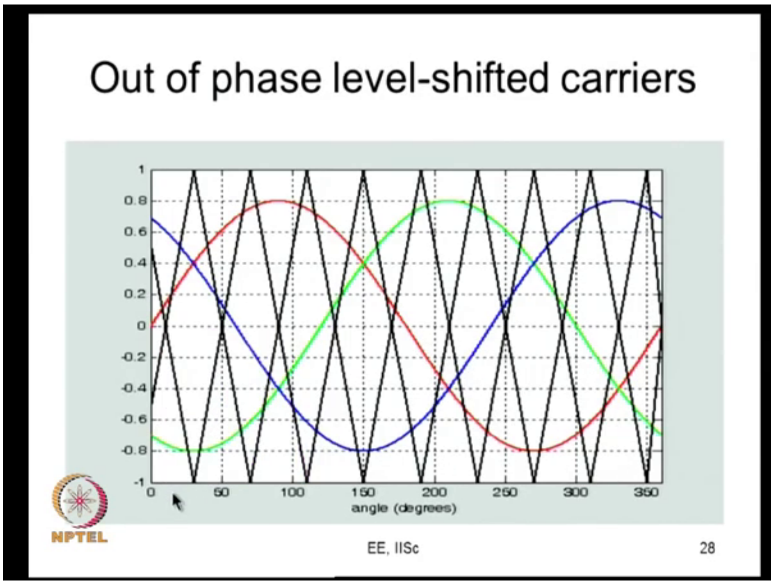

One particular case of phase shifting is have the two carriers out of phase. What I actually have is, this is the original top carrier, and this is the bottom carrier that two are actually out of phase, from picture you may not, I mean I could have plotted probably using two different colours, this black and this brown you would have known that. So, this is top carrier and this is a bottom carrier.

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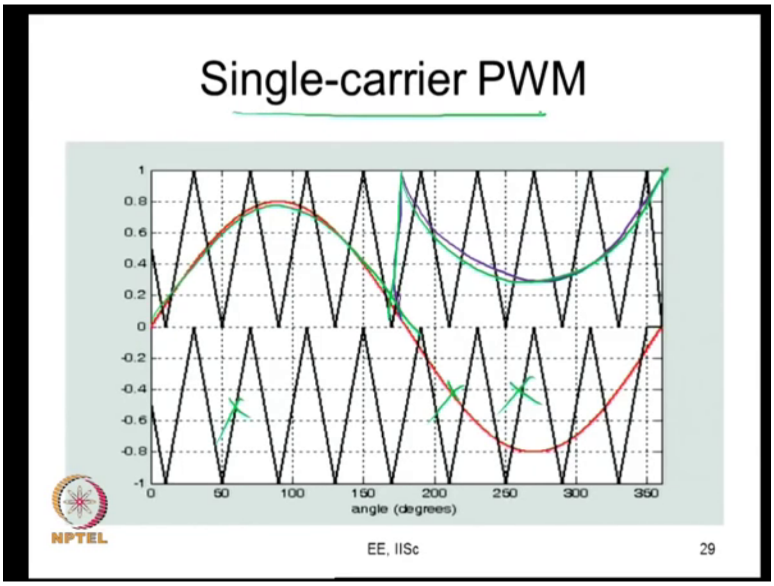

So, you can do this now. So, what you will see here is, you know there is yet another before we go into that, you need two carrier so there are lots of studies have been done.

There is also some places where they have used two modulating signals and a single carrier that is also there in the literature, I could give you the reference probably in the next lecture.

Now, if you want to do this, you see that there is no intersection between this and this. Again in this part this carrier there is no intersection. So, what you can actually do is, let us say you shift this fellow up, you shift this fellow up. What is this the R phase, I have just shifted up. So, the R phase signal is like this. Now I can actually compare. So, this should be at 0 crossing. So, what I can do is, I can ignore totally the lower part, I can ignore this part, I can ignore this part I can have a level shifted thing, which is like this and this part the sign is level shifted, and you can see that the instance of comparisons all will not change, if I do it properly you now I have not drawn it very clearly.

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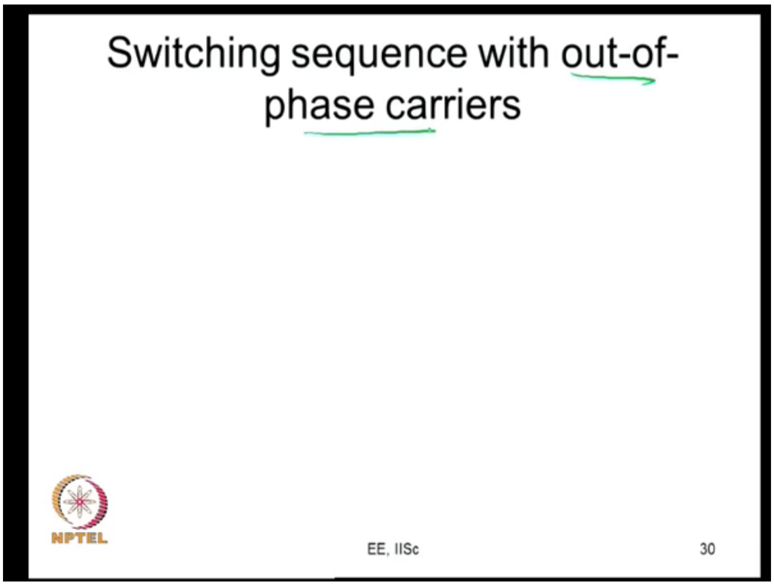

So, it you can use it using a single carrier PWM also, and you will see that when you can analyse this switching sequence which will do it.

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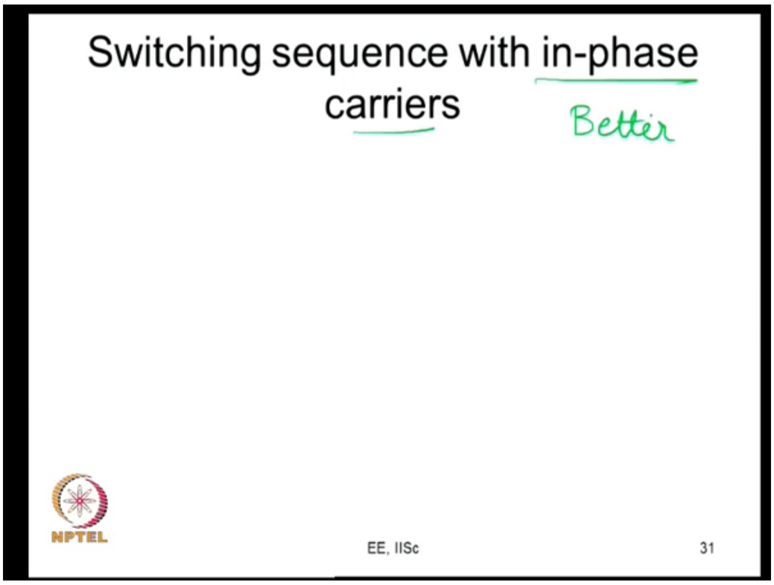

Next class this switching sequence with out of phase carrier, and the switching sequence for in phase carrier would be actually different, and you will find the in phase carrier is better in terms of the voltage error vector, it will lead to lower voltage vector. I would leave this as a home exercise for you; I will come back and anyway do it in the next lecture. So, next lecture we can get started of from this point, and I thank you very much for your interest and your patience, and I look forward to your continue participation in the next two lecturers.

Thank you very much.