Pulsewidth Modulation for Power Electronic Converters
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Lecture - 04
Multilevel converters – I

Welcome back to this lecture series on Pulsewidth Modulation for Power Electronic Converters. So, for most part of this course is going to be on; how are you going to produce those pulsewidth modulated wave forms for various power electronic converters and to be able to analyze the effects of those waveforms so, but. Firstly, we have been discussing about power electronic converters now. So, we earlier discussed about DC to DC converters then we moved on to DC to AC converters and in which we dealt with the traditional voltage source inverter and the current source inverter and today in this lecture you are going to be discussing so called multilevel converters or multilevel inverters.

These are also voltage source inverters. So, first what we will be doing is we will be briefly reviewing the voltage source and current source inverters which we looked at in the previous lecture namely the third lecture.

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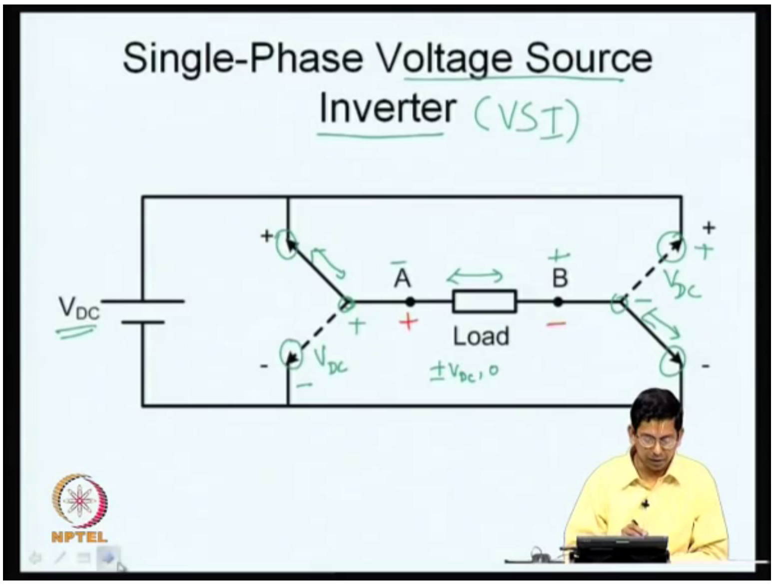

So, this is a single-phase voltage source inverter it is quite obvious, if you see that you have a voltage source here. So, you have a voltage source this is a DC voltage source this can convert DC into AC because it can very clearly see that if the switches are connected as shown here like this and here you know A can be positive with respect B.

If the switches are connected the other way as shown by this dashed lines then you can have B positive with respect to A, if both the switches, let us say both A and B are connected to the top DC bus are both of them are connected to the bottom DC bus, then the voltage across the switch can be 0 to thus you have voltages of plus minus VDC are 0 these are the 3 different instantaneous voltage of possible across this; since you have this positive VDC as well as minus VDC applied across this, you can see that it is actually what you get here is an alternative voltage.

So, you get an AC voltage here, now this AC voltage we will ensure that does not have any DC component, it may be non-sinusoidal, but it will not have any DC component. So, it will have only various sinusoidal components each of those sinusoidal components will produce some amount of sinusoidal current let us assume the load to be linear. So, when you say a load is linear you apply a sinusoidal voltage on that it will draw a sinusoidal current of the same frequency.

So, the load voltage may have sinusoids of different frequencies of fundamental in the harmonics, etcetera, we will be dealing with them later in greater detail, there will be corresponding sinusoidal currents are various frequencies in fundamental and the higher harmonics all the fundamental and higher harmonics are yet together would be some kind of an alternating current waveform which may not be exactly sinusoidal it can we can get closer to a sinusoid, if you do a good modulation if you do at a good switching frequency, but well it is going to be a sinusoidal you know it is going to be an alternative current now.

So, you have an alternative voltage depend across the load and alternative current flowing through the load hence is this qualifies the naming inverter. So, what you have DC what gets applied on the load is ac. So, it qualifies the term inverter now. So, it is a voltage source inverter because the DC source is available as a voltage source here it is available as the voltage source. So, it is a voltage source inverter and why do we call this is single-phase voltage source inverter because the load is a single-phase load.

So, this is a single-phase voltage source inverter many a times, this voltage source inverter is abbreviated invert we use the acronym VSI to denote an indicator voltage source inverter now. So, this load we presume that it is inductive it could be an r l load sometimes, it can also be an active load meaning there can be r l and a back came of being connected here, it could be a basically you know some kind of a single-phase motor kind of a source could be connected here this also possible that you know the this, but we presume that the load is inductive in nation and an inductive current should never be snapped open in the inductive circuit mean an inductive circuit you know part should be provided for the current flow through you cannot just open out an inductive circuit.

So, what we do there are load has to 2 terminals and both the terminals A and B are connected to the poles; one pole each and now you want a potential of either you know you want to connect either your positive DC bus here are the negative DC bus here, hence you have a single pole double through switch and the DC source is connected across the throws the load terminals are connected to the poles the load is inductive here they are connected to the poles and the DC voltage is connected across the throws these are the throws the DC voltages connected across the throws; similarly the DC voltages connected across these two throws.

So, what you need is you need certain switches which can function as a single pole double throw switch in this environment. So, the current basically can be in either direction as I pointed out earlier, it can be I from A to B or B to A. So, whenever I device this conducting let us say which is from it is in this position that is A as connected to the top, but a positive DC bus. So, this should be capable of conducting in both the directions and if this is the connection a is connected to the positive bus, then A is at the positive DC terminal and this is a the negative DC terminal and we have voltage at VDC a crossing. So, between a and the bottom through there is a switch which is now blocking a voltage the switching is in the half state it is blocking a voltage; voltage equal to what voltage equal to VDC.

Now similar observation can be made here if you think that you know B is connected to the bottom throw. So, if this can be conducting and it should be capable of conducting in both the directions. So, the top throw is at a positive potential with respect to the pole and the voltage between the twos VDC. So, it again needs to be you know a switch which can block a potential of VDC, but with only one polarity.

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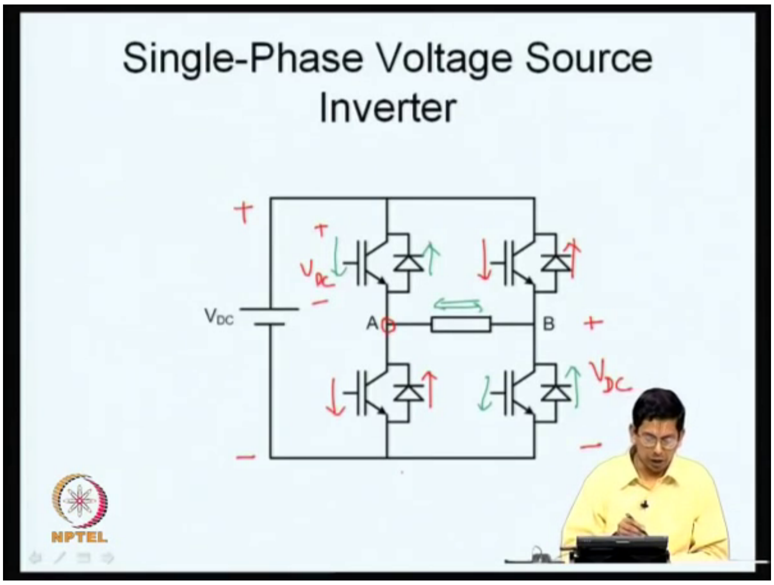

So, this is what we get here this is the electronic realization it can be conducting in either directions the load current can be flowing in either direction. So, the transistor can conduct in one direction the diode can conduct in this direction similarly this transistor can conduct in this direction and the diode can conduct, if you does not the opposite direction, if you look at the other state, if you look at the other state, then this transistor can conducting one direction and this diode can conduct in the opposite direction.

Again this transistor conducts in this diode conducts and the opposite direction. So, this converter has an ability to apply a potential which is equal to that of this positive terminal or a potential equal to that of this negative terminal at A, it is capable of connecting this pole A to either the positive bus or the negative bus irrespective of the direction of current flow the current flow could be from A to B or B to A; this is capable of connecting that is the attribute of a voltage source inverter it has an ability to apply a particular voltage out of a given set of voltages at a particular terminal irrespective of the direction of current. Now here we have only 2 voltages available which is namely this plus and minus?

Later on when we go to multi level inverter we will have more six terminals being available. So, this a inverter has an ability to apply either this plus or minus connect this pole A or the low terminal a to either this positive DC bus or the negative DC bus irrespective of the direction in which current flows. So, this is how you have a single-phase voltage source inverter you use bidirectional current carrying switches with unidirectional voltage blocking capability. So, if you have this kind of current conduction as I have indicted with the red ink here what happens is B is now positive and with respect to here.

So, the potential blocked here is going to be VDC. Similarly this tops which is also off; now it is positive with respect to here. Now you remember this is a single pole double throws switch this is what the top and the bottom devices together are called one leg of the inverter one leg of the inverter is a single pole double throw switch, we have realized a single pole double throw switch as two transistors which are switched in a complimentary fashionable tops which is on the bottom which is off in vice versa right. So, this is a single-phase voltage source inverter now.

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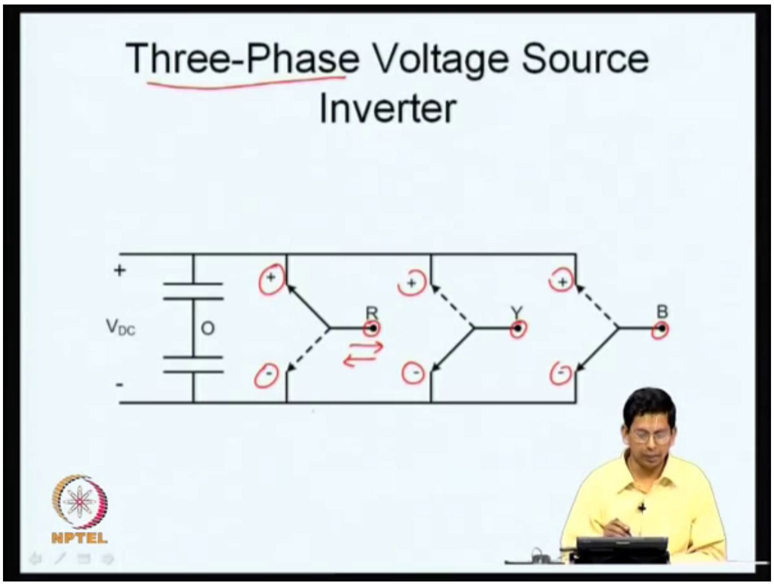

So, let us look at three-phase voltage source inverter what is a three-phase voltage source inverter instead of 2 legs it has 3 legs why; now you have a load which is a three-phase load the difference between this previous case and here is that was single-phase this is a three-phase there we had a single-phase load here, we are having a three-phase load a single-phase load has 2 terminals while a three-phase load has 3 terminals and the load is once again presume to be inductive and the inductive load has now 3 terminals. Therefore, the load terminals have all got to be connected to a pole each one terminal of the load let us call it r is connected to one of the poles another terminal of the load; let us call it Y is connected to the another pole and the third terminal of the load B is connected to yet another pole B.

So, you have 3 poles and every pole has 2 throws corresponding to each of it one throw is connected to the positive bus and the other throw is connected to the negative bus. So, one set of throws are connected together and connected to the positive bus another set of throws are connected together and connected to the negative bus. So, this is what you have now this is basically a three-phase voltage source inverter represented in terms of generic switches. Now we need to realize this electronically its similar to what we did before because the current that you have at R, let us say may be flowing in this direction are it could be flowing in the opposite direction the same story about Y and B 2.

So, once again you need switches between the pole and the throws which are capable of conducting in either direction and it all again needs unidirectional or unipolar voltage blocking capability.

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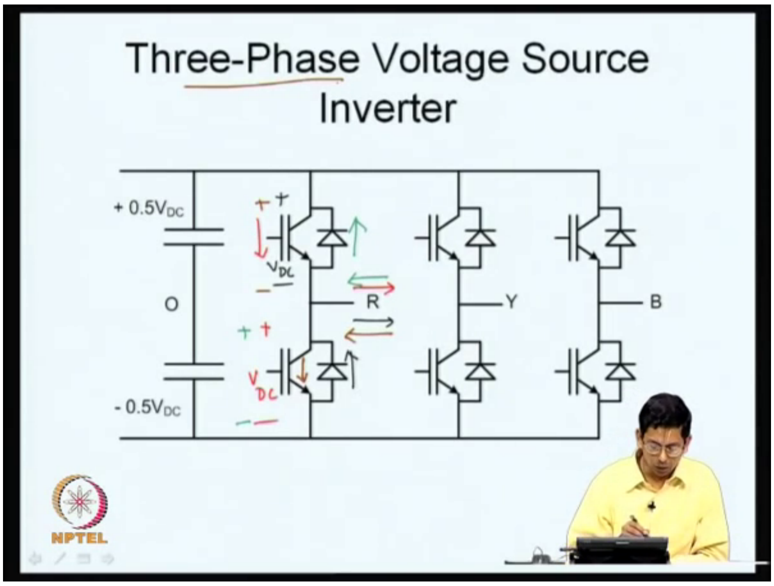

So, this is what we have now let us say R is conducting in this direction and let us say the top devices on. So, in that case you will find that this transistor is conducting and the bottom transistor will be blocking a potentially equal to VDC, let us slightly change the scenario and say that the current instead is flowing in this direction on the top devices on in such a scenario the top diode will conduct once again the bottom transistor with this R is connected to the positive bus the bottom transistor is going to be blocking a potential plus minus VDC like this.

Let us consider yet another scenario, let us say R is conducting in this direction and now the bottom transistors on the bottom switches on the top is off if the bottom is on you will have the conduction here and the diode is the one that will be conducting in such a scenario the top transistor is now in the off condition. So, the top transistor will be blocking a potential which is positive here and negative here on the potential is equal to VDC. Similarly, let us say you take yet another scenario let us consider yet another scenario where the bottom is on, but the current flow is in the opposite direction.

If the current flow is in the opposite direction you will have current flowing through this transistor rather than through the diode, but the potential yet R is equal to the potential of the negative terminal of DC bus. So, you will have the entire DC bus voltage appearing cross a top transistor. So, the top transistor is still blocking a potential of plus minus VDC. So, a whether there current is you know may be flowing in either direction. So, whichever is on either the top or the bottom should be able to conducting both the directions.

So, you use a transistor with an anti-parallel diode the transistor conducts in one of the direction the anti-parallel diode conducts in the other direction of the 2 let us say one of the miss conducting you know may be the bottom may be the top transistor or the top diode let us say the top devices conducting. So, the bottom device is now in the off state and it has to block a potential the bottom transistor simply blocks that potential it is only unipolar. So, you have VDC coming across that it blocks here. So, this is how you have all the 3 legs here and this is how this is a three-phase voltage source inverter and this is shown using IGBTs right.

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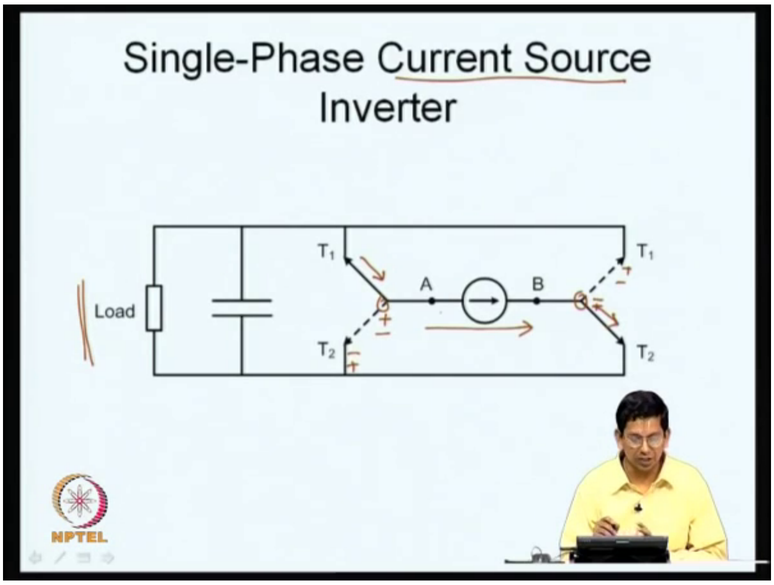

Now, let us say this is the single-phase current source inverter you can see that structurally it is quite similar to a single-phase voltage source inverter what I mean that one with only one difference in in a single-phase voltage source inverter you had a load connected between these terminals A and B and you had supply connected between these two terminals.

Now, what we have done is the load which was inductive there has been replaced by a current source here has been replaced by a current source here and the load is now capacitor and the capacitive load is connected across the throws the current source again the current flowing through a the current source should always be provided with a path you know, it can never be opened a current source can never be opened. So, the current pertaining, it should always have a path to flow through therefore, the 2 terminals of the current source are connected to one pole each and there are corresponding throws and the load which is now capacitive is connected across the 2 throws.

So, this is how we what we have a current source inverter now. So, you can see that this current is now its only unidirectional current it only flows in one direction now. So, if it is flowing in this direction, let us say this pole at a is connected to throw T 1, then it has to conduct in this direction it only has to conduct in this direction and not in the opposite direction similarly you take this connection between B and T 2 here it has to conduct only in this direction, it never has to conduct in the opposite direction. Now let us look at let us just consider this scenario where is connected to the top throw and B is connected to the bottom throw and current is flowing like this. So, what happens to the switch that comes between a and T 2 the switches off and what is a potential it sees it looks A; it sees the load voltage.

The load voltage could either be you know positive or negative. So, what it sees is the load voltage which is an alternative voltage it could be of either polarity similarly about you know the same thing about this switch also which comes between B and T 1 here it is also and the off state and what is the potential it sees it again sees the load potential because B is connected to T 2 which is connected to the load. So, this is connected to the one end of the load this is physically connected to the other end of the load. So, it may be like this it has an alternating potential that it sees it kept T 1 can be positive or B can be positive. So, it sees an alternative.

So, now what you need is between a and T 1 for example, or a and T 2 for example, you need a switch which conducts in only one direction in one particular direction, but you need a switch which can block voltages of either polarity is this is the realization.

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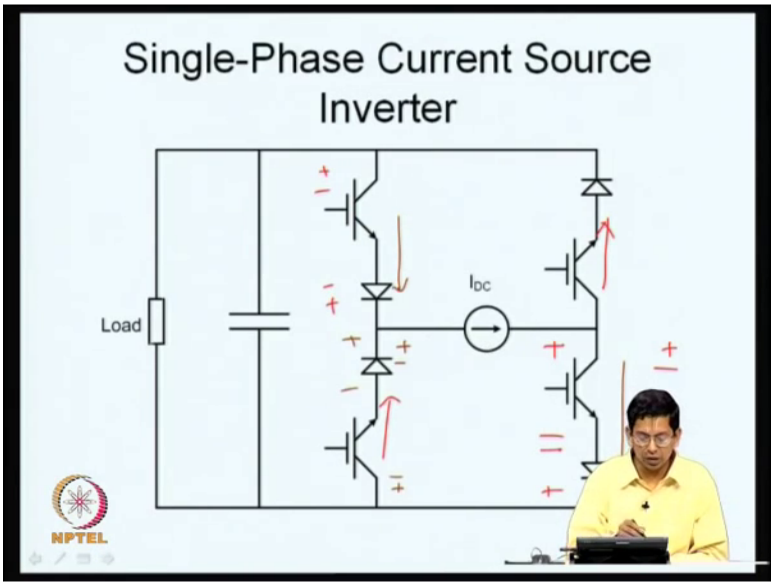

So, you can say if the current is flowing in this direction as it is you will have if these two devices are current flows in this direction and these blocks a potential which can be of either polarity a potential of this polarity is block whether diode and the potential of opposite polarity could be block by the transistor. And therefore, you have a bidirectional voltage blocking capability here.

Similarly, you can look at the other scenario where these two devices could be on. So, in that case current flows through this and here and these two switches are now in the off state which could be blocking a bidirectional voltage which could be a either polarity. So, this is one electronic realization of a current source inverter. So, a single I mean unidirectional current and bidirectional voltage blocking as I mentioned earlier thirstier is a natural option to do this, but we can also use a transistor in series with a diode. So, called anti series connection why anti series as I mentioned before you may have something which can block in one potential and something you know another element which blocks in the opposite potential.

So, let us say we take this transistor this transistor is capable of blocking with this potential there has the diode is capable of blocking with an opposite polarity while both of them conduct in the same direction, I will both of them conduct in the same direction. So, you call it a anti series connection and you go and for this in you get this turn up right. So, this is slightly redrawn what you have here is you see one transistor in one direction another one what we have done is we have redrawn and the source is here and the load is there we have broad the source to the left hand load here. So, this is one leg of a current source inverter very similar to one leg of the voltage source inverter.

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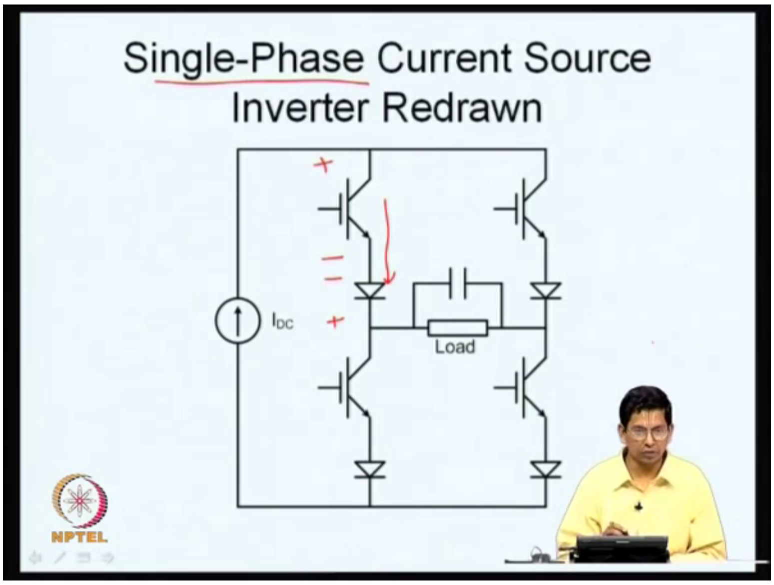

So, one leg of a voltage source inverter if you remember a tried you know the fundamental differences where the load was presume to be inductive there here the load a capacitance is been connected across the load. So, even if the load has some r l r whatever you know if it is an r l r load or whatever it is overall, it is capacitive a nature now and you have a DC current source; now apart from these differences as for as the switches are concerned earlier you had a switch which is capable of conducting in both the directions.

Now you have a switch which is capable of conducting in only one direction earlier you had in a voltage source inverter you had a switch which can block or which needs to be its needs to block a voltage of only a particular polarity here you have a transistor which can block with this polarity and the diode which can block with the opposite polarity the 2 of them in connected in series you have a switch which has a bidirectional voltage blocking capability now.

So, this is just we previous circuit has been redrawn. So, 2 things this is only to see that you can add one more leg like this if you want a this is a single-phase current source inverter if you want a three-phase current source inverter all that you need to do is draw one more leg like this and between those 2 legs also let us call is R Y and B that will Y and B also you have capacitance between R and B also you have capacitance you have loads connected across them there is a little more about single-phase and three-phase current source inverters.

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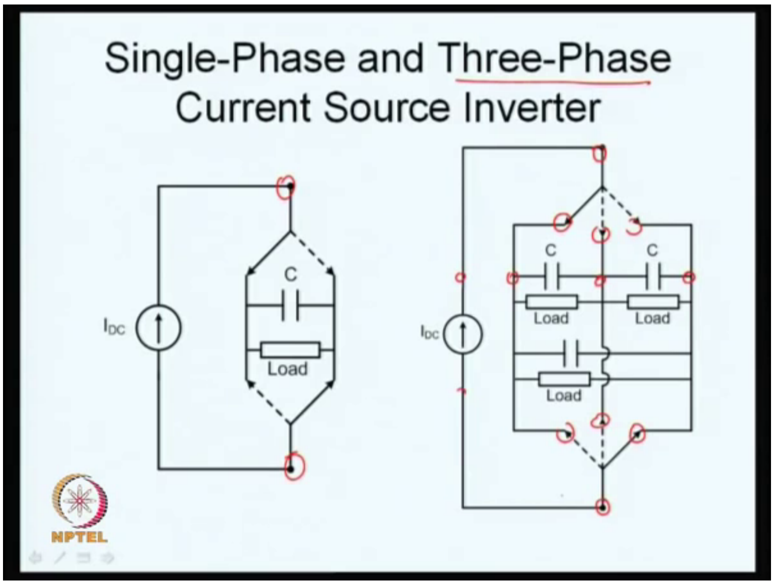

So, I have just drawn a single-phase current source inverter using generic switch now.

As I said you know it is just that the same thing redrawn. So, this is a current source has 2 poles has 2 terminal. So, these are connected to the 2 poles now and the load which is capacitive in nature is connected across the throws right. So, if you want to realize a single-phase or a if we want to realize a three-phase current source inverter the load is now three-phase it is the capacitive load. So, these are the load terminals these are the 3 load terminals. So, the current source still has only 2 terminals. So, the current source is connected to every terminal of the current source is connected to one pole each. So, the number of poles gets decided by the number of terminals of the current source as I was mentioning in the previous lecture now.

The number of terminals of number of throws is equal to the number of load terminals the load being capacitive now. So, you have 3 terminals of or 3 throws here. So, it is a single pole is a single pole double throw switch here, whereas it is single pole triple throws switch in the case of a current source inverter. So, we see such certain differences from the time when we are dealing with a DC to DC converter in DC to DC converters we only had you know single pole double throw switch, but now you are seeing a single pole triple throw switch in the case of a three-phase inverter and once again you know first in in those cases the conduction was only in one direction whereas, in the voltage source inverter earlier we saw conduction in both the directions.

We saw that the current carrying capability could be in either direction now in again you know the source there we are slightly expanding and expanding and going higher than this norm. So, you had from a point very use only a single pole double throw switch which are all single quadrant switches we again have single pole double throw switches in a voltage source inverter like here; like here, but they have bidirectional current carrying capability you have in a current source inverter again you may have single pole double throw switch unidirectional conduction, but bidirectional voltage blocking capability and you if you go to a three-phase current source inverter you will need 2 numbers of single pole triple throw switches.

Now, all this is you know to recollect and so that you know we have our ideas clearer before we launch on to whatever we need to see today now.

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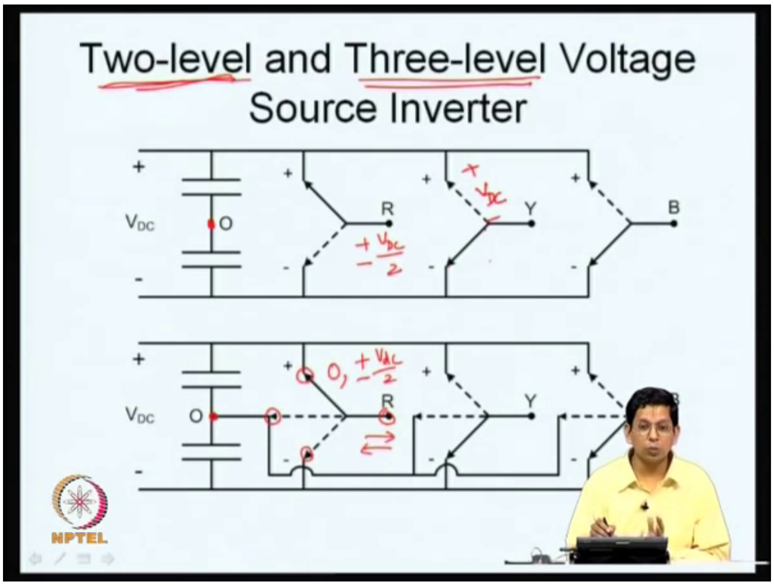

So, that is about a multi-level inverter now multi-level meaning see. So, for all that we have been seeing is we call that as a 2 level inverter we have seen a voltage source inverter little earlier, we call that a 2 level voltage source inverter because let us say this potential R this take this pole R and look at the potential here. And this O which is call the DC bus neutral or the DC bus mid-point is a convenient point for us to express all the voltage is mean as the reference it express all the voltages and various nodes now.

This may not be physically available, but theoretically it is easy for us to mention now. So, the potential at R with respect to O can be plus VDC by 2 if R is connected to the positive throw if R is connected to the bottom throw, it can be minus VDC by 2. So, the potential at R can take 2 values either plus VDC by 2 or minus VDC by 2 and it can take only 2 values, hence we call this as a 2 level voltage source inverter alternatively let us say if the same R, we have this R connected to a pole of a single pole triple throw switch rather than a single pole double throw switch in the same pole, but connected to 3 different throws.

So, it is a single pole triple throw switch now a single pole triple throw switch is available and you can connect it to any of these 3 throws now in this case what happens the middle throw it is connected to the midpoint here, here the midpoint is available for connection and a connection is made in this case of a 2 level inverter the midpoint is only kind of emotional, let us only use for a theoretical pops it is not a physical point you may need you may not have that point available for you to make a connection sometimes you may sometimes you may not, but here you have this point is for electrical connection. So, you connect this 2 the midpoints of the third throw or the middle throw right.

So, now you what you have a; so single pole triple throw switch and we are O here can be if the top is connected it can be plus VDC by 2 if R is connected to the bottom throw it can be minus V DC by 2 as before if R is connected to the middle throw it can simply be 0. So, we are O can take 3 values now namely plus VDC by 2 or minus VDC by 2 as in previous inverter 2 level inverter and also it is 0. So, it can take 3 different voltage levels.

And therefore, we call this as a 3 level voltage source inverter. So, you have set of 3 DC potentials available which could be applied at this pole namely plus VDC by 2 or 0 or minus VDC by 2 again this inverter it is an inverter it has a load it is a voltage source inverter and the load here is presume to be inductive and being in a c load the current carrying you know the conduction could be in either direction it could be either flowing out of the pole or flowing into the pole.

So, this switch or this converter should be capable of applying any of the 3 potentials either plus VDC by 2 0 or minus VDC by 2 at R independent of the direction of current flow at R because it is a voltage source converter. Now, what kind of switches do we need is the next question that we have going to look at for the next 15-20 minutes are so often this lecture. Now let us start this let us just look at every leg is now single pole triple throw switch the pole is connected to one of the throws and between the pole and the other throw 2 throws the switches are open.

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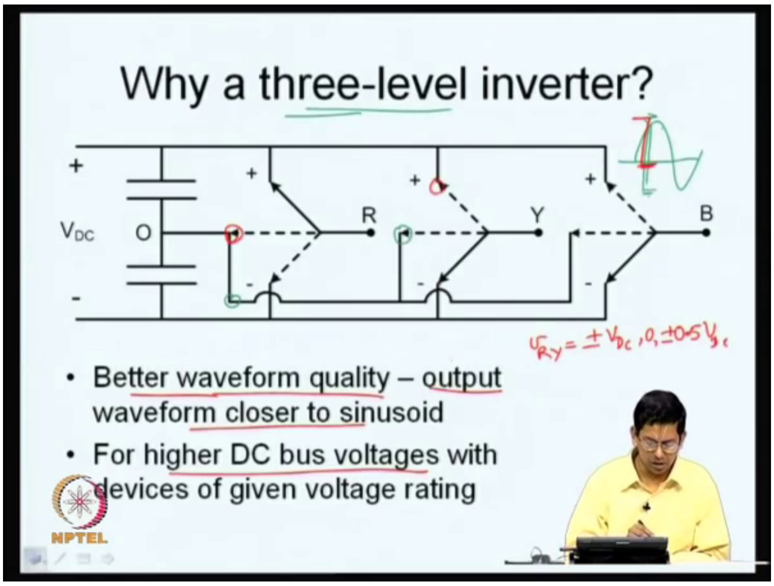

Let us look at a single I mean a O how to realize before we you know look at how do we go about realizing let us try and understand why we need a 3 level inverter at all because this is basic motivation and also this is required for us to go about doing this realization partly now one reason is it can give a better waveform quality that is the potential at R. For example: if you want the potential at R Y and B let us say first say the potential between R and Y this is one of you know 2 of this load terminals and V R Y is basically a line to line voltage applied on the load you want this voltage to be as sinusoidal as possible you wanted to be as sinusoidal as possible. So, you want the voltage to have as many levels as possible in the case of a 2 level inverter it can be either plus VDC or 0 or minus VDC these are the only 3 voltage levels possible between V R Y you should take V R Y; V R Y can be either plus or minus VDC or 0 in case of a 2 level inverter.

In the case of a 3 level inverter you have not only plus VDC 0 you can also have plus or minus 0.5 VDC let us say R is connected to the top throw and Y is connected to the middle throw. So, what you have between R and Y is plus 0.5 VDC not only that let us say R is connected to the middle throw and Y is connected to the bottom throw once again you can get plus point five VDC. So, if there are 2 different ways by which you can realize plus 0.5 VDC. Similarly, let us say you want to realize V R Y equals minus

0.5 VDC then what you can do is why can be connected to the top throw and R can be connected to the middle throw.

This will give you minus 0.5 VDC alternately you can also connect Y to the middle throw and R to the bottom throw once again it will give you minus 0.5 V d c. So, a 2 level voltage source inverter can give you only 3 different instantaneous values of line to line voltages plus V DC 0 minus VDC here you have five different values plus VDC plus 0.5 VDC 0 minus 0.5 VDC in minus V d c. So, you are the sinusoidal voltage you want is at the desired voltage and what we have going to apply is not going to be, it is not going to be the same as the a desired voltage, but we can get closer to that because this plus 0.5 VDC and minus 0.5 VDC levels are available.

Also since there are five different voltage levels are available for this V R Y some authors ten to call a; this as a five level inverter. So, you need to be careful when someone tells you a five level or a 3 level we need to understand what is talking about, but in this course we will always use this is 3 level inverter the number of levels we will define on the basis of the number of levels of the pole voltage rather than the number of levels are the line to line voltage here the pole voltages still has 3 levels only in therefore, we call this now. So, the better quality waveform is because more number of levels are possible. So, you can follow a sign wave a little more closely than you could do with fewer levels.

Let me put it even the other way let us say if we are why has to be sinusoidal one way is V R O should be sinusoidal and V Y O should also be sinusoidal. So, if V R O should be sinusoidal once again you know you have a sinusoid here you have a sinusoid here now you have only potentials of plus VDC minus VDC and 0 now you have 0 also for V R o. So, you have 3 different levels available. So, let us say at some instant this is your sign that you want, but what you apply is plus VDC. Let us say this plus VDC is here and if you do not have plus VDC the next level is minus VDC you may be switching from here all the way down to minus VDC you will do all this clearly in a later lecture this will be minus V DC and if I am applying minus VDC here.

The error between what I desire that is the sinusoidal waveform and the error between what I actually apply which is minus V DC is very high the error is VDC plus V m I mean where V m is if I say is the peak voltage of this sinusoid that I want now whereas, instead of applying instead of applying 0 if I apply only like this I shown by the red ink if I apply only 0 the instantaneous error is now much lower. So, you can see that the instantaneous error between the ideal sinusoidal waveform and the actual applied waveform could be lower in the case of a 3 level inverter than in the case of a 2 level inverter this is because more number of voltage levels are available.

So, hence we say the output waveform could be closer to sinusoid and therefore, we can say that it has a better waveform quality the harmonic destruction could be lesser here. So, there is better waveform quality now another important reason why we use such a 3 level inverter is to be hand able to handle higher DC bus voltages how do you do that see you have devices of various voltage ratings there could be small MOFSETs which are rated for 60 volts or 100 volts or 120 volts we have some IGBTs and IGBTs could be rated for 600 volt and 1000 volt and 1200 volt and so on.

You go on higher and higher it is difficult to find devices of substantial voltage rating. So, we have something called as medium voltage drives in motor drives we have low voltage motors and we have medium voltage motors this low voltage motors. Typically have voltage ratings of the order of hundreds of volt and you know just about one kilo volt are less than that medium voltage motors have voltage rating of the order of a few kilovolts something like a let us say about 2.2 kilo volt.

For example, now if you want to drive a 2 point kilovolt motor using an inverter unit switches unit switches of adequate voltage rating earlier we just saw in a 2 level inverter case, but unit the switches which could block a potential of if you take here the switch if Y is connected to the bottom throw then between the top throw and why a potential of VDC appears it has to block a potentially equal to VDC this VDC if you want to 2 point 2 kilovolt motor we are VDC could be something close to 3 kilovolts.

So, you may not get a switch which is capable of blocking 3 kilovolts you will get you would you mean quite often you might be getting switches which can you know whose voltage ratings are substantially lower or even if you have a switch which can which has a voltage rating higher than 3 kilovolts it may be 2 expensive. Therefore, what you have is you have devices of given voltage rating with this you want to build an inverter whose DC bus voltages significantly higher. So, you would normally going for series connection of devices in such cases going in for a 3 level inverter is better than going in for a series connection as I will point out now.

Voltage level I mean a 3 level inverter can you do equally well and it is also better in some sense as we will see a little later now. So, you can actually handle now you can build an inverter whose DC bus voltages substantially higher than the device voltage ratings that is one of the points that we are trying to make here.

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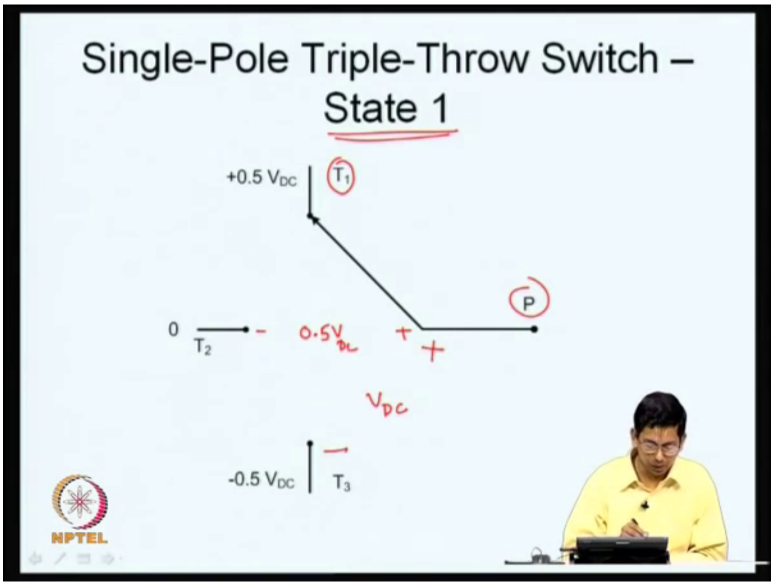

Now, let us go further to see how we do what we do now. So, with regard to the electronic realization what we need to realizes the single pole triple throw switch. So, we need to look at the individual pole to throw connections pole to individual throws connections between them and before there let us look at the different states.

So, this is what I call as state one it is a single pole triple throw switch the pole can be connected to the 3 throws T 1 T 2 or 3 3 in this case P is connected to T 1. So, I am calling this as state one. So, this is state one in this case what happens P and T 2 P and T 2 are left open again P and T 3 are also left open. So, P and T 2 is open, but it block some voltage what is that voltage is equal to voltage at P is equal to that of T which is equal to 0.5 VDC and the voltage at T 2 is 0. And therefore, what we have is plus minus 0.5 VDC the switches I mean the switch are the set of switches that come between P and T 2 are in the off condition and they are blocking a potential they are blocking a potential of this polarity as indicated when they are blocking a potential of 0.5 VDC, right.

Now, how about the switches between P and T 3 again they are off they are blocking a potential they are blocking a potential with P positive with respect to T 3 and the potential difference is not 0.5 V d c, but it is a entire VDC because P is connected to 0.5 VDC and T 3 is connected to minus 0.5 V dc. So, the potential differences equal to V DC this is state one of the single pole triple throw switch we are talking about now.

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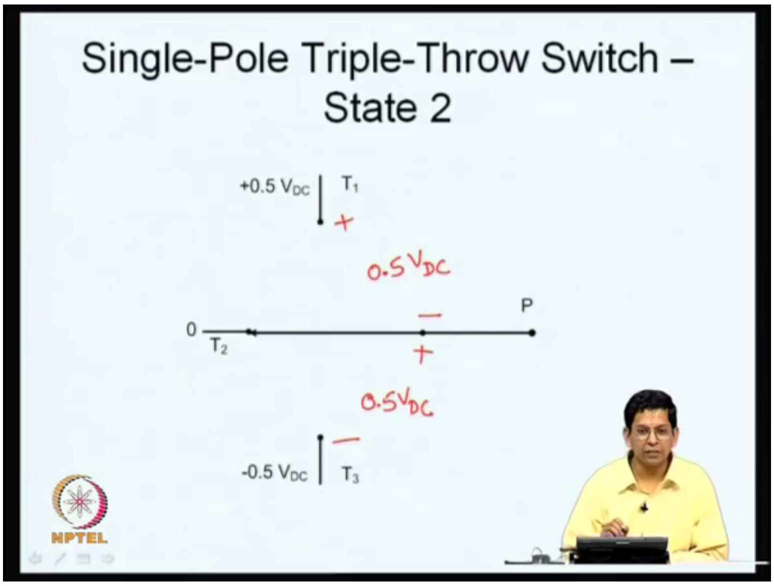

Let us look at state 2 this is state 2 here as we can see P is connected to the throw T two. So, between P and T 1 the devices are off. Similarly between P and T 3 the devices are off. So, between P and T 1 the devices together are blocking a potential where T 1 is positive with respect to P because T 1 is connected to plus 0.5 VDC P is connected to T 2 this is connected to 0 and the potential between these two is 0.5 VDC.

Again between P and T 3 the switches are off the devices are off. So, the potential is P is positive with respect to T 3 and the potential difference between the 2 is once again 0.5 VDC.

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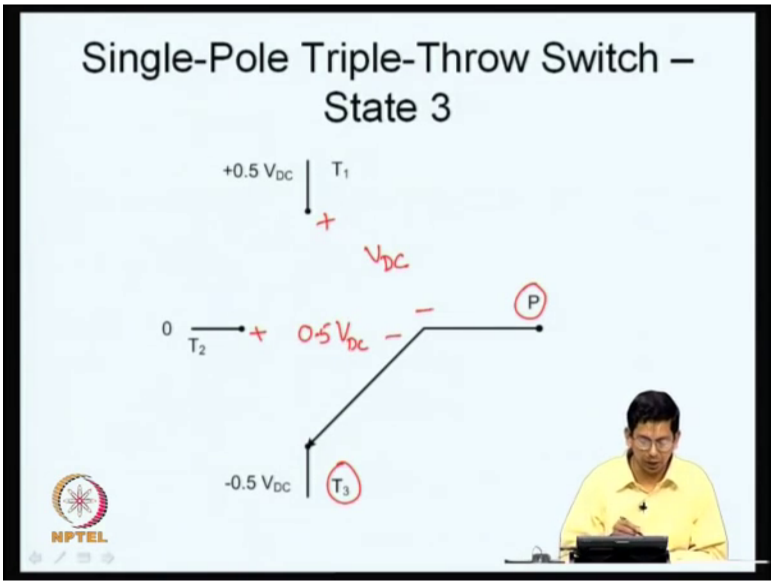

Once again we go to state 3 the pole is connected to the bottom throw T 3 and between P and T 1; T 1 is positive P is negative and the potential differences VDC. So, these switches are in the off condition and they blocking a potential equal to VDC. And similarly the devices that come between P and T 2 block a potential which is equal to 0.5 VDC here as indicated here. So, this is what you have now

So, let us go further and try to realize between P and T 1; let us try to see the kind of devices we need between P and T 1.

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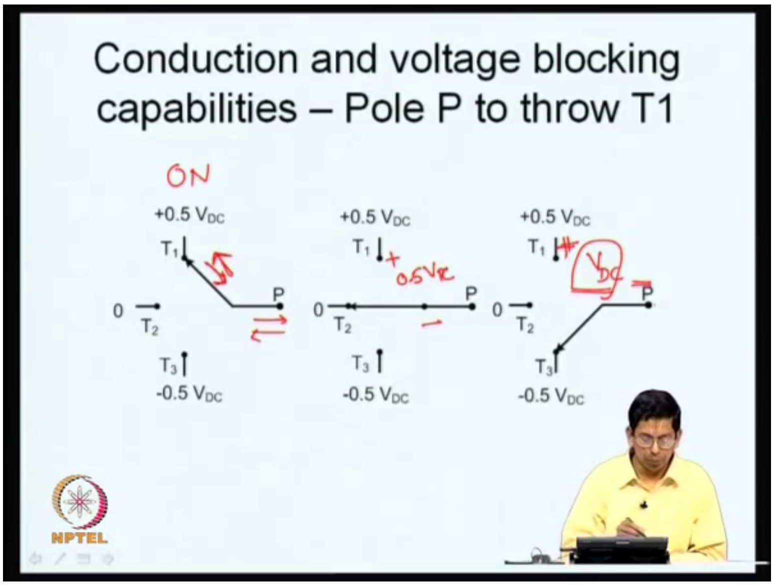

So, between P and T 1, I have no given on all the 3 stage together. So, this is the on state this is the on state as for as the switch concern between P and T 1 is concerned now. So, the current can be in either direction. So, this switch should be capable of conducting in both the direction. So, this is the requirement on the part of the switch are switches the devices that come between P and T 1, they should be capable of conducting in either direction now let us say P is connected to T 2 what should be done between P and T 1 as I just mentioned before P and T 1 should be able to block a potential equal to 0.5 VDC with polarity as indicated here T 1 is positive with respect to P.

Then in the state 3 once again if you look at P and T 1 it is off and what is the potential T 1 is positive with respect to p, but there voltage. Now is VDC in this second state the switches blocking a voltage of I mean voltage equal to 0.5 VDC in the third state it is blocking a voltage equal to VDC which is higher than the first one. So, what we need together is a switch which is capable of conducting in both the directions when it is in the off state and which is capable of blocking a potential equal to VDC of this polarity has been indicated here T 1 positive with respect to P this is what we expect this is the conduction in the these are the conduction in voltage blocking capabilities of the devices that come between pole P and throw T 1.

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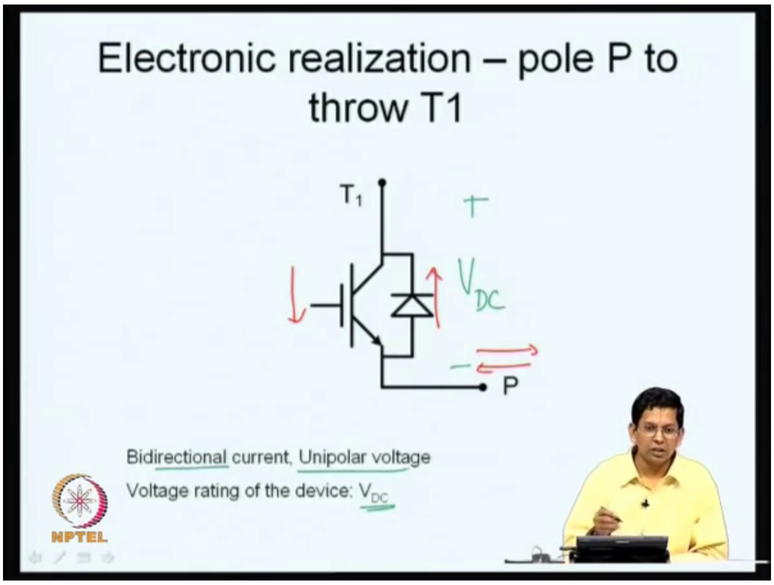

So, how do we realizes electronically this is quite similar to what we saw in a voltage source inverter? So, the current could be flowing in either direction and therefore, we have a switch which is capable of conducting in both the directions which is you know transistor with an anti-parallel diode. So, these two can be in conducting both the directions when this has to be off let me indicate with a different color ink when this switches off then T 1 can be positive with respect to P and the potential block needs to be VDC. So, this needs to be devices you can have a; if you have a transistor and a diode like this and in the devices are rated for VDC it should be possible for you to be block this potential.

So, the voltage rating of the devices VDC if the you need bidirectional current unipolar voltage and the voltage rating of the devices VDC. So, let us move further this is only one step towards the realization of single pole triple throw switch.

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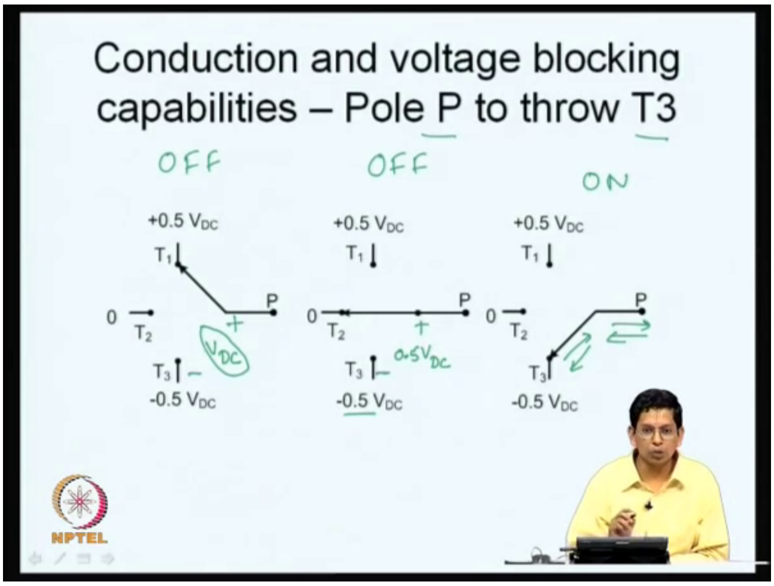

Now, let us look at the next one let us look at the conduction in voltage blocking capability is between the pole P and throw T 3. So, what we are looking as pole P and pole T 3 this is now off state again pole P and throw T 3 it is now in the off state whereas, this is the on state in the on state you know. So, there is always anyway current keeps flowing through the pole and in the on state it flows through T 3 between P and T 3 you need a bidirectional current carrying capability.

So, once again you need a switch which is capable of conducting in both the directions this is quite similar to what we had between pole P and throw T 1. So, here if you say it is off, but if you look at the potential the pole P is connected to throw T 1 and therefore, to plus 0.5 VDC. And so this is positive and throw T 3 is negative and what is the potential between the 2 this is plus 0.5 VDC this is minus 0.5 VDC therefore, you have VDC is the potential coming cross here once again you look at P and T 3 in this state pole P is positive with respect to throw T 3 now P is connected to 0 and T 3 is connected to minus 0.5 VDC. Therefore, the potential here coming the between the 2 is 0.5 VDC.

So, the higher of this 2 if you consider it is VDC. So, what you need is you need a set up switches which are capable of conducting in both the directions here between P and T 3 and again when they are in the off state it should be capable of blocking a potential equal to VDC.

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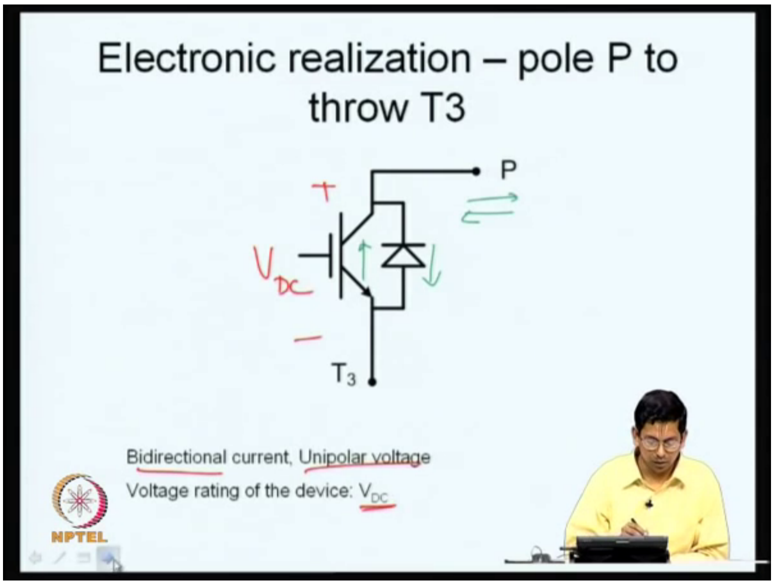

So, this is what we made P quite similar to what we got before if does conducting these can conducting in these two directions if it is blocking it can block a potential like this. So, it is bidirectional current and unipolar voltage and the voltage rating required is VDC.

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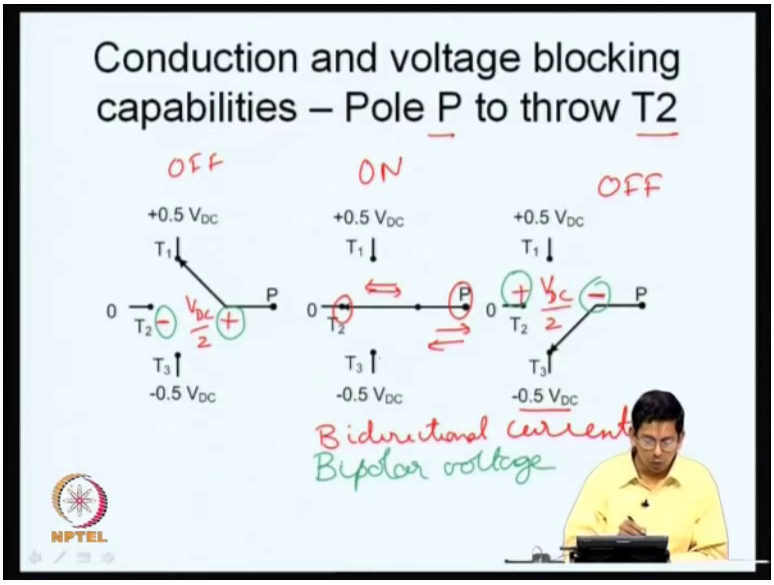

Now, let us move on we are we are still you know you only inching our way towards the overall realization let us look at the conduction and voltage blocking capability is between pole P and throw T 2.

Pole P is connected to throw T 2 here this is the on state whereas, it is open P and T 2 are open here; here also. So, these two are actually off states in the on state, you know current can be flowing in either direction. So, between P and T 2 current has to follow in either direction. So, once again what you need is you need a bidirectional current carrying capability you need bidirectional current carrying capability current needs to be bidirectional how about the voltage. Now let us look at it a little carefully it is off here P is connected to T 1.

Therefore, you know P is positive and T 2 is negative with respect to T what is the potential that comes between the 2 P is plus 0.5 VDC and T 2 is 0. So, the potential differences 0.5 VDC are VDC by 2. The potential differences only VDC, but to not VDC at P is positive with respect to T 2 let us look at this third connection here pole P is negative because it is connected to the bottom throw which is connected to the negative bus and T 2 is positive and what is the potential difference between the 2 VDC by 2.

So now, look at the difference now look at the difference here the polarities as indicated and look at the polarity here. So, between P and T 2 P and T 1 was similar to what we had in a 2 level voltage source inverter P and T 3 was also similar to what we had in a voltage source inverter, but P and T 2 is a little different know how it requires a bidirectional or a bipolar voltage blocking capability you need a bipolar voltage blocking capability, it is a bidirectional current it is bidirectional current when it is on and it is a bipolar voltage blocking when it is off. So, you need this P 2; T 2 to be a 4 quadrant switch.

Now we discussed the 4 quadrants switch on the very first lectures. So, you need actually a 4 quadrant switch here to realize P and T 2, whereas P and T 1 and P and T 3 are only bidirectional switches I mean by 2 quadrant switches with bidirectional current connection. So, now let us go about you know we are still inching our way. Let us look at what could be a practical or a feasible realization it is a 4 quadrant switch.

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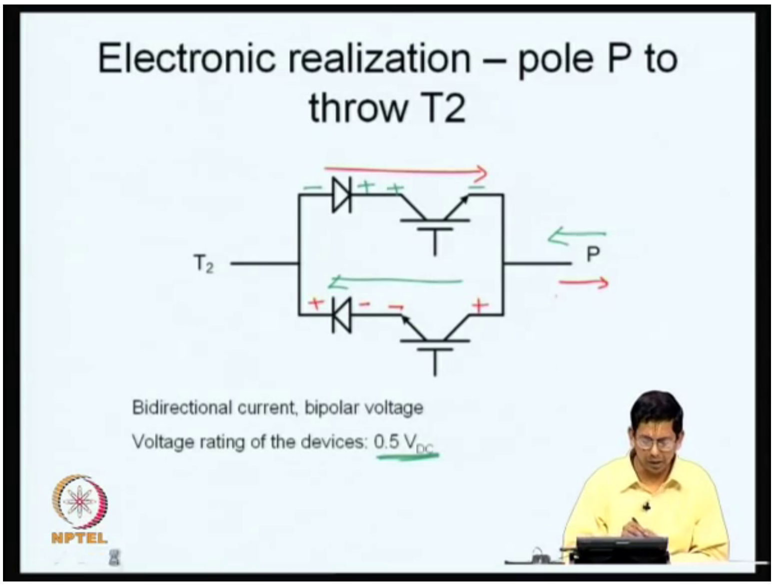

So, it can conduct in either direction. So, let us say it can be conducting either this way or this way let us first take that it is conducting in as indicated by red ink now if it is conducting in by as indicated by red ink. Then this is the direction of conduction this is the direction of conduction how about the voltage blocking these two devices are in the off state this is capable of blocking a voltage, where the collector has positive with respect to the emitter this diode is capable of blocking voltage where the cathode is positive with respect to the anode. So, together you can say that they these two devices in series can block any bipolar voltage signal this is what we need the 4 quadrant switch, you need this bidirectional.

So, let us say if the current direction is the other way that say the current direction is other way then what happens is these two conduct these bottom transistor on the diode conduct and now the top collector is capable of blocking a potential as indicated here and the diode is capable of blocking a potentially if this the 2 in series together can block a potential either way. Now the voltage rating required is only 0.5 VDC you need to block a potential of only 0.5 VDC. So, you do not need a switch which is capable of blocking VDC are whose voltage rating is equal to VDC please remember the voltage rating of the switch has always got to be substantially higher than VDC or 0.5 VDC because there are going to be over voltage spikes and several things, but still this is an important factor. So, this is one of the reasons why you choose. Now for example, if you need about let us say 700 volt DC bus which is very common in India, we use 400 or 415 volt kind of motors.

We want to drive this motors we will commonly use a DC bus voltages is equal to about 700 volts. Now for 700 volts voltage rating a voltage bus, it is very common to use devices that are rated 1000 volts or 1200 volts 1200 volts is even more common I think that is probably because they available we have devices now. So, if you use 1200 volts for 700 volt rating here if you say your DC bus voltage is only 350 volt for example, you will still you know require or something like 600 volts. So, for a 700 volt DC bus rating you will still use 1200 volts, because of practical considerations like now we are ignoring all those practical considerations and we are just looking at the device voltage rating as it should be in an ideal scenario.

So, here what we see is these devices need not be rated for the entire DC bus voltage. It is enough with their rated for half the DC bus voltage. Now thus we have some idea; now between how the switch should look like between P and T 1 P and T 2 and P and T 3 that is put them together now.

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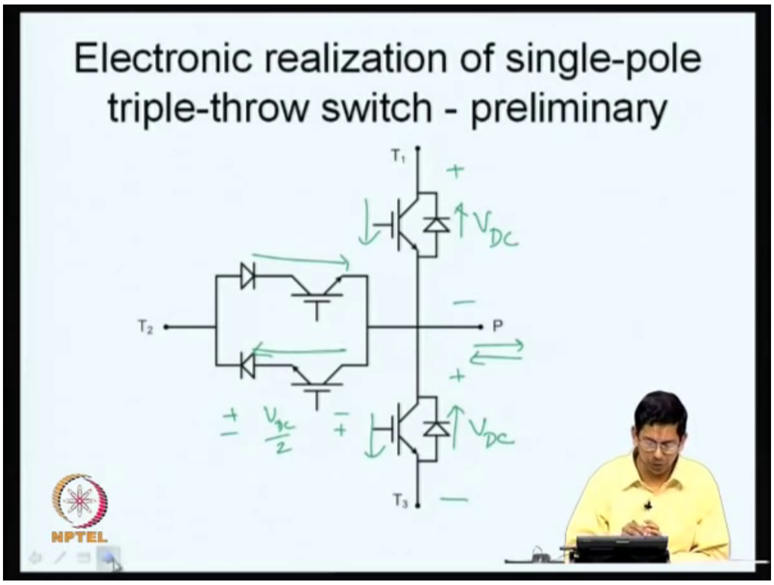

So, all the switches are capable of bidirectional current conduction because through pole P the current conduction can be in both the direction. You can see that all the switches can conduct in both the directions this can conduct this way this can conduct. This way this transistor like this this diode like this can conduct then this direction this can conduct an opposite direction.

All these 3 switches are capable of conducting in both the directions now about voltage blocking well this can block only with this polarity this also can block only with this polarity, whereas these switches can block with both the polarities. So, these are 2 quadrant switches the top on the bottom the top 2 middle is the 4 quadrant switches I mentioned earlier now. And the voltage rating of P 2 T 1 has to be VDC here again it has to be V DC, whereas here it is only 0.5 VDC, it has to block only 0.5 VDC. So, we want to realize a single pole triple through switch not with devices of voltage rating VDC and some devices with VDC by 2.

We want to realize this with all devices whose ratings are only equal to VDC whose ratings correspond to VDC by 2.

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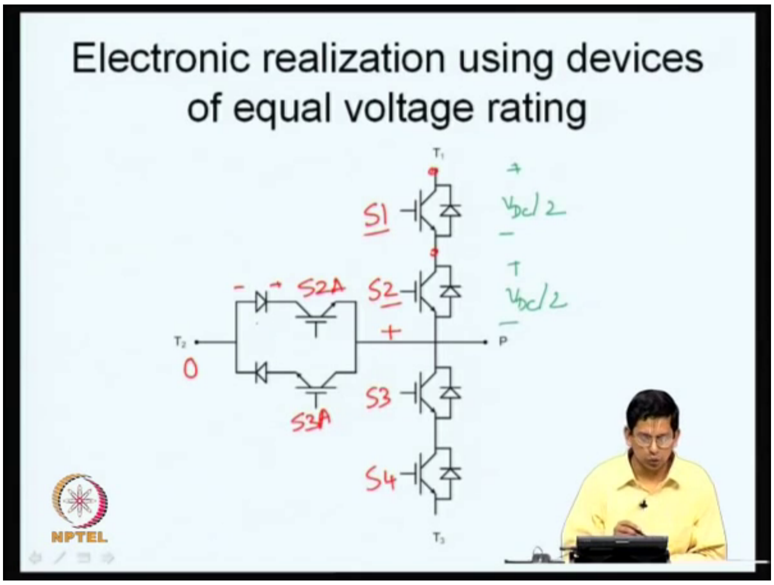

So, what we do is like this going for a series connection just to start with. So, that one of them is capable of blocking a potential VDC by 2 and the other one is also capable of blocking a potential equal to VDC by 2. So, the 2 together in series can block a potential equal to VDC this is just an idea we are still moving towards what is going to be our final circuit. Now, again the bottom devices also, you have 2 of them in series now. So, now, what you have we have realized the single pole triple through switch starting from fundamentals has we have been doing for DC; DC converter. And then for the 2 level voltage source inverter and current source inverter we have been doing this.

So, now we have come to a some kind of a realization now. So, you have a also we are able to realize this using transistors and diodes that are rated for only VDC by 2 and nothing higher than that not equal to VDC. So, you use devices of lower ratings to handle a DC bus voltage which is substantially higher right. Now what do we do? Do we need all this; how is it going to be operated if pole P is to be connected to throw T 1, let me just give some let me just give some names for this let me call the switches S 1 call this is S 2 this as S 3 this is S 4 let me call the switches S 2 A and S 3, I have there some meaning behind this I am calling; I am not calling it has something different, but I am saying it is something because it something related to S 2, let us get there in a short well from now.

If you want pole P 2 be connected to throw T 1 which such a realization which such kind of switches what do we had to do both S 1 and S 2 have to be on and both S 3 and S 4 have to be off and similarly S 2 A and S 3 A also needs to be off now. So, again if we have to connect to the bottom throw T 3 S 3 and S 4 should be on and all the other switches should be off if we have to connect pole P 2 throw T 2 only these two switches S 2 and S 2, S 3 A should be on all the other force should be off right. So, this is how you realize, but the question now is do we really need this kind of a realization cannot not be a little simpler how can it be a little simpler let us look at and individual switch now why do we need a switch.

We need a switch number one to make a contact number 2 to break a contact or you know to open. So, either it provides a connection between 2 of its terminals are it opens out. So, let us say you take the switch S 1 and S 2. Now S 1 has a role one is to connect the throw T 1 to this terminal here the other function it has is to open to serve has an open circuit between open connection between S the these two terminals. Now let us say if you want to connect pole P to throw T 1 you have to both of them have to be on if you want to disconnect pole P and throw T 1 it is not necessary that both of them needs to be on it is enough if S 1 alone is half and S 2 could still be on.

Only if both the switches are on it could be conducting now. So, there is some redundancy here. Now similarly let us say if S 2 A is you know these two are conducting these two S 1 and S 2 are conducting. Now if S 1 and S 2 are conducting what is the potential here at the midpoint plus what is the potential here this is 0. So, who is blocking the voltage between these two is at the transistor as is at the diode it is actually the diode that is blocking this potential. So, this transistor does not have a significant role in blocking the voltage it blocking is actually done by diode.

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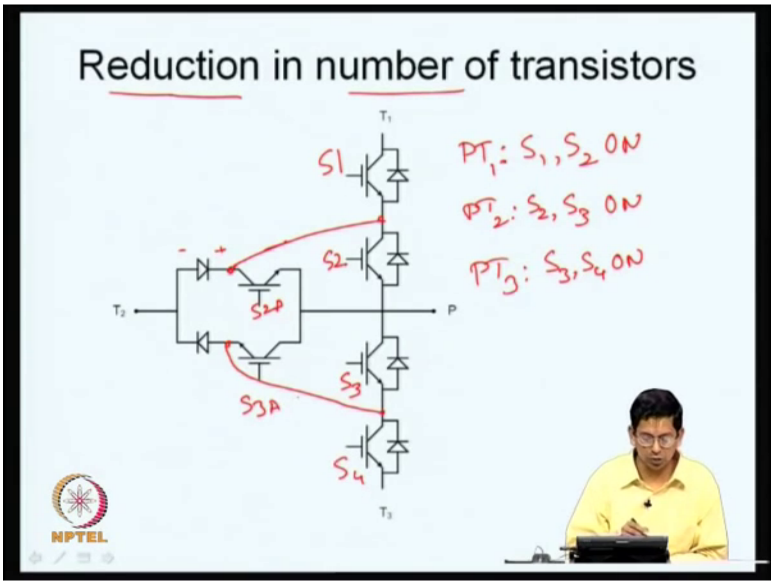

So, we go to the question whether we can have any reduction in the number of transistors whether we can have any reduction in the number of transistors now.

So, you know there seems to be some kind of redundancy because if P and T 1 needs to be opened out it is enough just to have S 1 opened need not have to open both S 1 and S 2. Similarly if you know P and T 2 are opened if P is connected to positive through T 1 then this is what serves as the open circuit the diode is what is providing the voltage blocking capability the required not be other way. So, the question is what happens if we connect these two what happens if we connect these two it can still work pole P to throw T 1 if you have to do what we do is and you know S 1 and S 2 are on you have S 1 and S 2 are on pole P and throw T 2 will be connected now for P could T 1 to be connected what we do is S 1 S 2 on.

For pole P and throw 2 to be connected what you do is you have S 2 on and let us call this as S 3 and S 4 we can also have a similar connection coming between here now. So, if you have this S 2 and S 3 are on it can provide a connection and with S 1 being off and pole P to T 3 you can say S 3 and S 4 are on in the other switches are off. So, you can actually you know connect these two are you can replace these two switches these two transistors what I had called as S 2 A and S 2 by a single 1 and S 3 A and S 3 by a single transistor I shown here.

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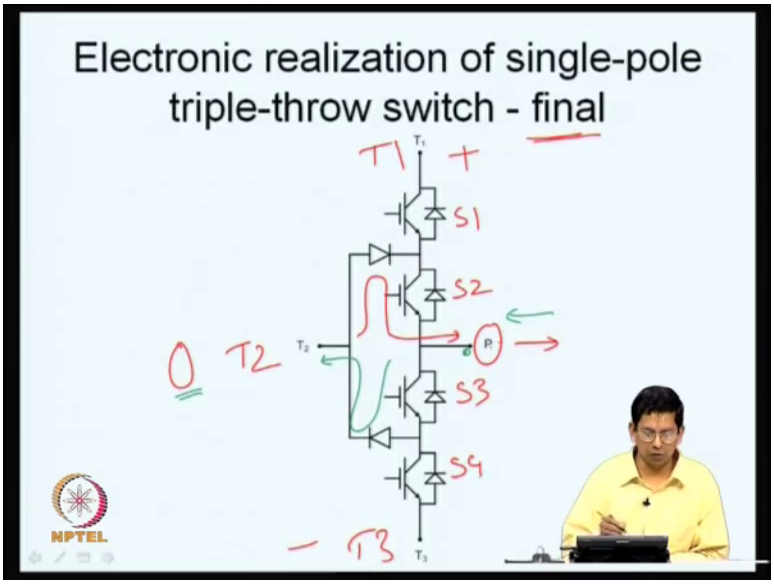

And now this is what I would call as a the final realization of a single pole triple throw switch now this is the pole P this is the throw T 1, this is throw T 2 this is throw T 3.

This is connected to the positive terminal this is connected to 0 this is connected minus. So, you have S 1 and S 2 on for connecting the pole to the top throw S 3 and S 4 on for connecting the pole to the bottom throw the other switches are off if you have to connect the pole to the middle throw then you keep S 2 and S 3 on. So, the current flow if at pole is like this if you are connected to T 2, then the current will chose to flow like this if a current is in the opposite direction if it is in the opposite direction then it could flow like this. So, this provides a bidirectional current path. So, you are able to connect this DC bus neutral to the pole P and therefore, one of the names that is given to this circuit is a neutral point clamped inverter as we will just see little later and you use a diode to make this connection. And therefore, it is called a diode clamp inverter now.

So, what you find here is S 1 and S 3 are actually complimentary if S 1 is on S 3 will always be off and vice versa if S 1 is on S 4 will always be off and vice versa. So, this is a neutral point clamped are diode clamped inverter.

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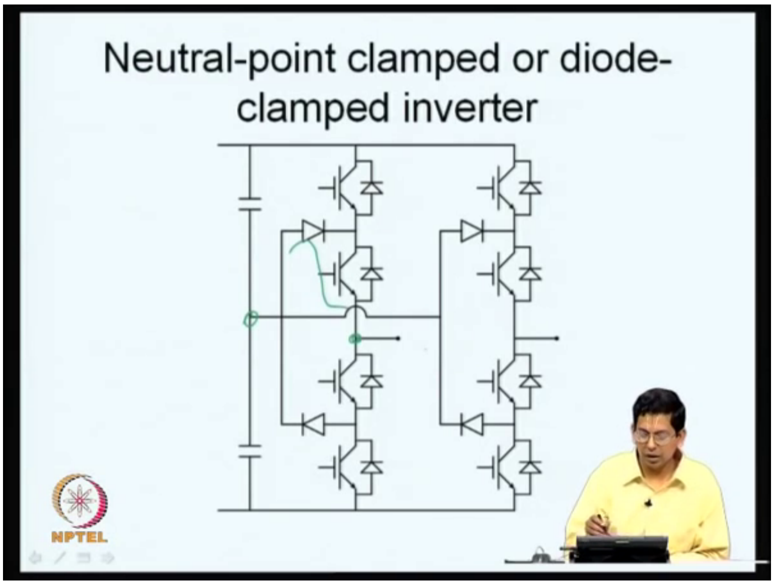

Because as I just mentioned the DC bus neutral can get connected to this pole through these two by keeping S 2 and S 3 on and are it is called diode clamped inverter because the diodes are used to clamp that off we just look at our last slide. So, this is I have just indicated for single-phase loads here. So, you it is just a connection for meant for a single-phase do not you; this is the you have 2 different legs here you could also have 3 different legs potentially for a 3 level diode clamped inverter

We will discuss more on multi-level inverter there are several other configurations are also that are available now. This is one of the most commonly used comb combination that is a neutral point clamped are a diode clamped inverter. We will be discussing these further and other configurations of multilevel inverters in the next lecture. So, thank you very much for your patience and your interest. And I look forward to you further lectures and I hope you form this interesting and useful.

Thank you very much.