Pulse width Modulation for Power Electronic Converters
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Lecture – 05
Multilevel converters – II

Welcome back to this lecture series on pulse width modulation for power electronic converters.

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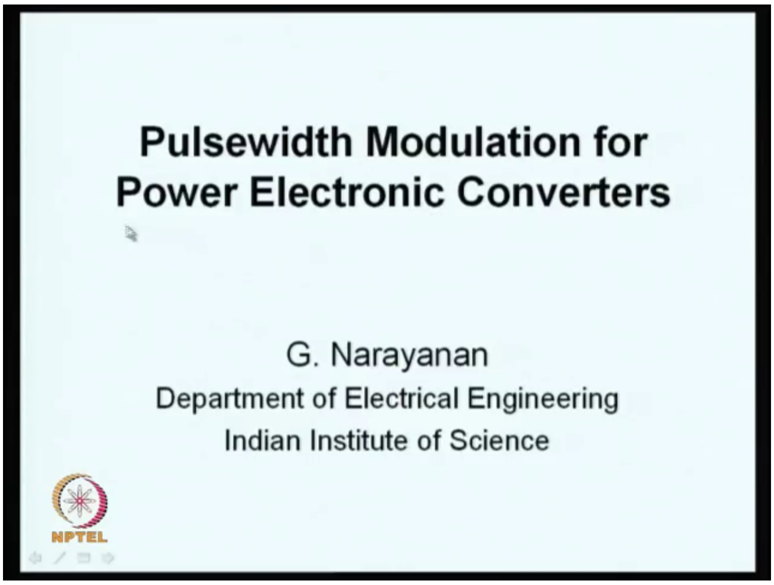

Now, we have been discussing power electronic converters for quite a while now over the last 4 lectures and this is probably going to be the fifth lecture. Now, as we discussed earlier power electronics involves control, conditioning, conversion of electric power. Electric power might be available in the form of DC or AC of a particular frequency in the amplitude. You might want AC voltage or DC voltage of another amplitude of AC of some other frequency. So, we now we need electric power conversion because many a times the load that we have might have a different power supply requirement from what is available, like that is what we have been discussing all through. We may have 230 volt 50 hertz mains available, but the load might need 110 volt DC, so you need rectification.

You might have a 400 volt 50 hertz 3 phase AC available, but your motor induction motor might need a 200 volt 250 hertz supply voltage. So, in such kind of situations you need you know conversion is required and that is why we have power electronic converters now and here the conversion is primarily done based on switches.

So, first we discussed about various switches, electronic switches like very semiconductor devices such as diodes, thyristors, IGBTs, MOSFETs etcetera which can act as switches. Then we went on to converters, how do you use switches to do a DC to DC conversion. From DC to DC conversion, we moved on to DC to AC conversion and in DC to AC conversion we looked at voltage source inverters and current source inverters, I mean DC could be available either as a voltage source or current source. So, depending on that you might need a voltage source inverter or a current source inverter. So, we discussed both possibilities.

Then in DC to AC conversion we have been moving to another step which is called multilevel converters and we discussed multilevel converters you know some aspects of multilevel converters last time and we are going to continue. This is the second lecture on multilevel converters now.

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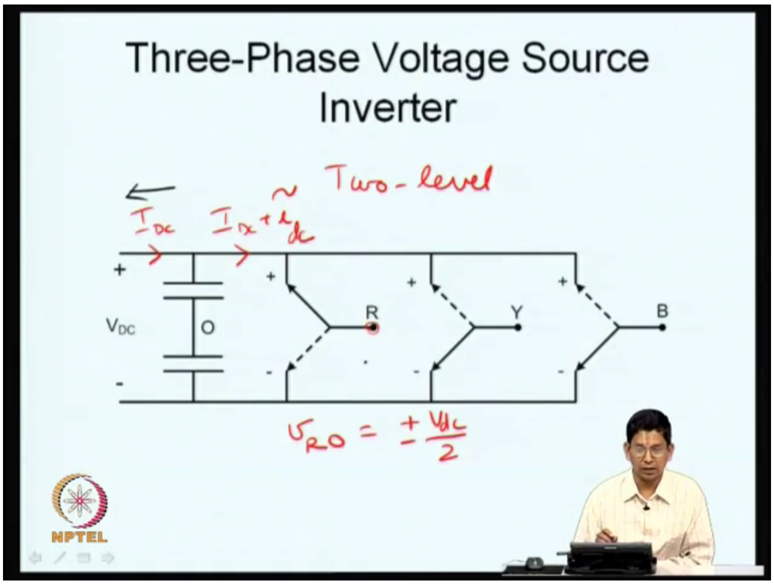

So, let us take a look at what is a conventional two-level voltage source inverter. This is the standard 3 phase two-level voltage source inverter. I would call this as a two-level voltage source inverter because of one reason; I would call this as a two-level voltage source. Why? If I have my, you know all these are single pole double throw switches. Let me consider this point R, which is a pole, which is the midpoint of a leg. This V R measured with respect to the DC bus neutral O can only take 2 values here, either plus V dc by 2 or minus V dc by 2. Hence, we call this as a two-level voltage source inverter.

Now, in this case you know all these are, so, r is connected either to the positive bus or negative bus through a single pole double throw switches. For every leg you have a single pole double throw switch and these 3 poles are connected to the loads and the loads are presumed to be inductive here and inductance current through an inductive circuit should never be opened. You should always provide path for it to flow through. Therefore, the load terminals are connected to the poles and the pole is going to be connected either to one throw or the other throw therefore, there is a path is always going to be available here now.

And as we were also remarked earlier, this is really a bidirectional power convertor. Power can actually flow in both the directions. It is not necessary that needs to flow from the DC side to the AC side. You have a DC supply here, let us say current can be flowing like this and here this is DC and this can be DC plus ripple flowing like this, let me call this as I DC, let me call this as some I DC plus I tilde, certain ripple current. I will also call tilde DC just to say that it is on the DC side now.

So, what we are going to see is you know and the ripple is flowing through the capacitance. Now, the power flow is in which direction, it is from the DC side to the AC side. That is what it means now and here again you would see the power factor. On the load side if you look at the fundamental voltage and the fundamental current, they will be close to one another their phase will be close to 0 or within 90 degrees plus or minus and therefore, powers flowing in the opposite direct in one direction from DC to AC.

Can power flow in the opposite direction? Of course, power can also flow in the opposite direction if you make sure that this I DC is now in the opposite direction if you see this I DC is in the opposite direction and if you look at the phase relationship here the voltage and current could have a phase difference of 180 degrees let us say, instead of 0 degrees. So, that basically means powers flowing in the opposite direction.

It is actually a bidirectional convertor. Power can flow in either direction. That is the point that I would like to make now and this is called a voltage source inverter because you can apply certain voltage at this pole irrespective of the direction of current that is flowing through.

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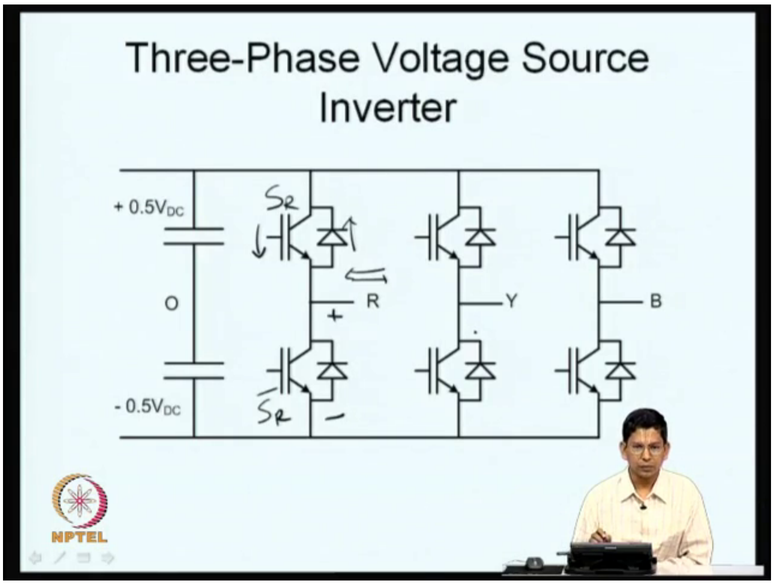

The current can be in both the directions. This is what we take took into account while designing the switches. What did we do? We realized the single pole double throw switch using to such IGBTs. These are capable of conducting in both the directions.

So, and when this is conducting like this, this will be blocking a potential. Lower transistor will be blocking a potential equal to the DC bus voltage with polarity as shown here. The same way when the bottom is conducting and the top is turned off. So, it depends on whichever direction the load current flows, depending on the direction of load current it is either the transistor or the diode which is going to conduct now.

So, this is how you realize a single pole double throw switch if you call one of them as SR and if you call the bottom as SR bar. So, these 2 are actually switched in a complementary fashion, if the top is on the bottom is often vice versa. So, it is a single pole double throw switch now. And R can take either plus 0.5 V DC or minus 0.5 V DC with respect to O. Similarly, Y can take either plus 0.5 V DC or minus 0.5 V DC with respect to O. The difference between R and Y can be either plus V DC or 0 or minus V DC that is what we have.

Now, we want to see whether between R and Y, we can have only plus V DC 0 or minus V DC. Why not have plus or minus 0.5 V DC for example.

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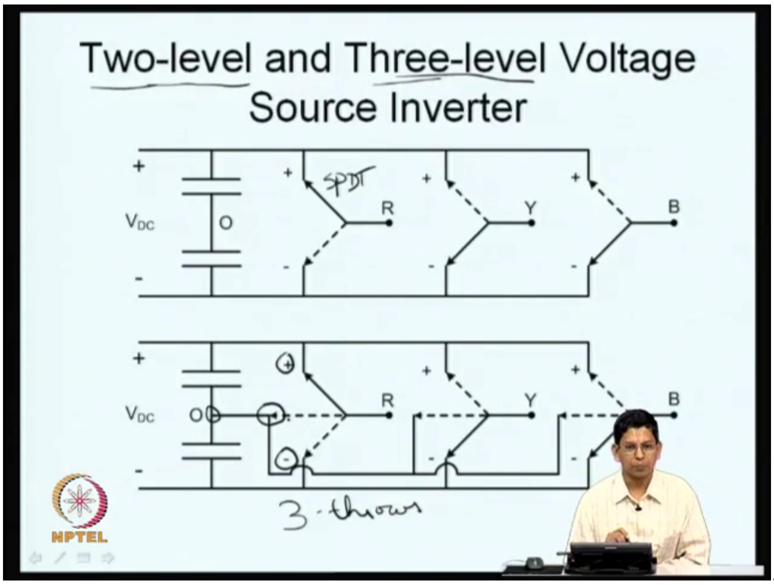

So, that is if you want to do something like that then you need, what we call as a three-level voltage source inverter. A two-level is what we saw before and a three-level is now what we are going to look at. So, now, this is the two-level voltage source inverter, where every leg is a single pole double throw switch now. It is all a single pole double throw switch. There are 2 throws here. If you look at the lower picture, there are 3 throws here. As before the load is presumed to be inductive and therefore, the load terminals are connected to the poles. The poles are always connected to one throw or the other therefore; there is will always be some path available for the load current to flow through.

Now, what we have is R this pole can be connected to, let us say, the positive throw plus or it can be connected to the middle throw 0 or it can be connected to the bottom throw minus. Earlier it could be connected only to the positive DC bus terminal or the negative DC bus terminal. Here, it can now it could not be connected to the DC bus midpoint. Now, we are able to connect it to the DC bus midpoint also. So, we use a single pole triple throw switch and the third pole or the middle pole is used for doing that now.

So, this is a three-level voltage source inverter whenever you are talking of a three-level, four-level or anything you know 3 or above we call it by the generic name multilevel voltage source inverter. Generally, we would be in this course, by enlarge, when we say multilevel inverter we would mean a three-level inverter. It is also possible for you to have a single pole 4 throw switch, for example, 4 different voltage potentials here, instead of 3 potentials plus 0 and minus. It is possible to have 4 different potentials and have a single pole 4 throw switch.

Similarly, in the DC you can it is possible to have 5 different potentials and have a single pole 5 throw switch. So, this would be called four-level inverter and five-level inverter and so on. So, all these are multilevel inverters, but in this course when we say multilevel inverter, we usually mean a three-level inverter, that is true even otherwise. So, now, we look at you know we, in fact, already looked at how do we realize this single pole triple throw switch.

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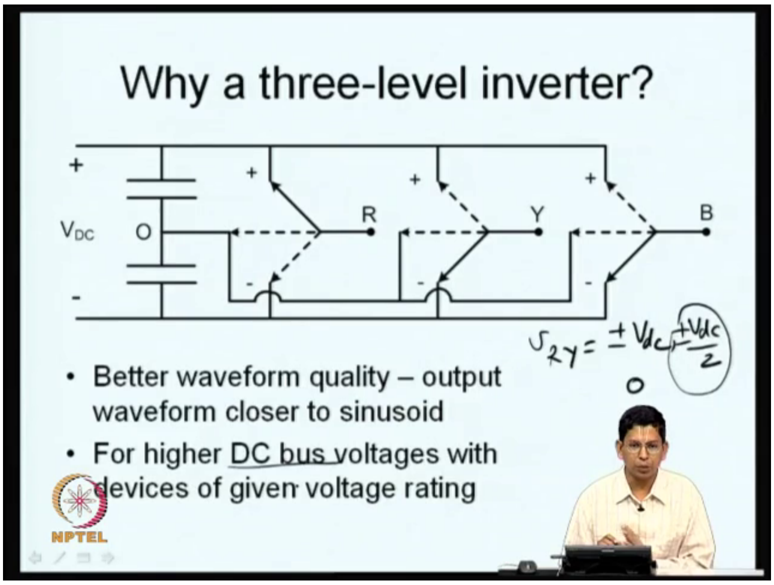

So, now before that we just wanted to see why a three-level inverter just to reinstate our idea, that is, I mean the concepts. R need not be just connected to plus or minus it can be connected to 0 also. Similarly, if you look at the potential between R and Y for example, V RY can take either plus V DC or minus V DC as in a two-level inverter it can also take either plus V DC or minus V DC by 2, besides 0. These are all the various values that it can take. In a two-level inverter it is only plus or minus V DC or 0. In a three-level inverter this one is extra; it can be plus or minus V DC by 2 also.

So, there are more number of voltage levels available at the output and therefore, it is possible for you to follow a sinusoidal waveform better. See what you ideally want at the output is a sinusoidal waveform you are never going to get that now because you know we are using DC and we are trying to produce AC out of DC. So, there is going to be always some amount of non sinusoidal components, it is going to be distorted now. We want to move closer. So, one way is you know if the voltage levels this provides a certain additional voltage levels or intermediate voltage levels, so that you can follow a sine voltage waveform better. We will discuss more of this later.

Now, another important reason why you want is, your DC bus voltage may be high. In India, we have 3 phase motors which are typically rated something like 400 volts to 440 volts RMS line-line. In some other countries it could be 110 volts or 208 volts or whatever. We may also have you know when you go to higher and higher power levels the motor voltage rating may also be higher. It could be higher than a kV for example; it can be a few kilo volts. So, such motors are called medium voltage motors and to drive a medium voltage motor you might need an inverter. In such as kind of a scenario, what you will have is, three-level inverter or a multilevel inverter is quite useful here.

Now, you will have a higher DC bus voltage because your motor voltage is now higher. Therefore, correspondingly you also need a higher DC bus voltage. If you have a higher DC bus voltage you need switches which can block so much of DC voltage, whenever they are in off state. You need switches whose voltage ratings are substantially higher than whatever DC voltage that you use. If your DC voltage is something like let us say about 3 kilo volts or 5 kilo volts or 6 kilo volts it will not be possible for you to have you know you may not have devices to this now.

So, one thing with that you might do is go in for series connection of devices. So, that you know you can match the required voltage rating, but better than go in for series connection is such a multilevel configuration now. So, this is again something that we will see a little later. So, here you need only devices of voltage ratings V DC by 2 as we will see shortly. So these are the 2 primary reasons I mean to handle higher DC bus voltages and to produce superior waveform quality, output waveforms or superior quality are the 2 primary reasons why one would probably go for a three-level inverter just you know basic motivation now.

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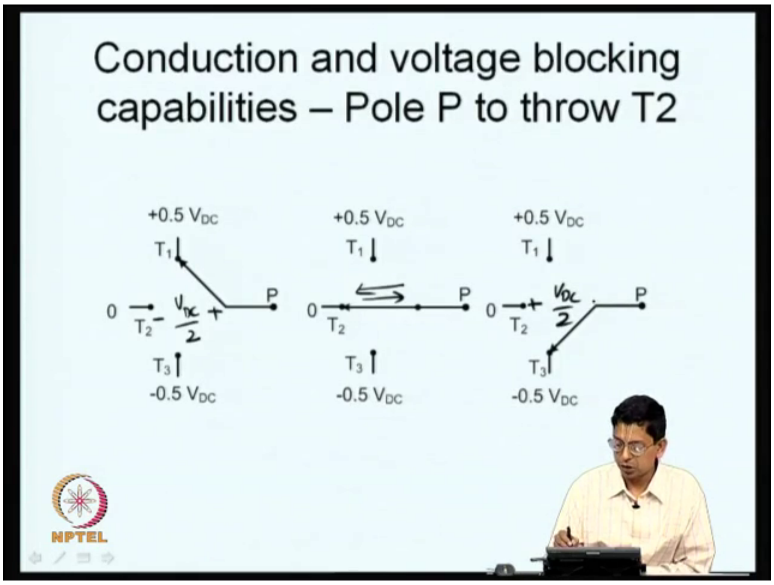

We have been looking at actually how you would realize this switch. If you want to realize one part of switch pole P to throw T 1, the 3 different states are available here. In this first case pole P is connected to T 1 now.

So, the current can be bi-directional therefore, the current between P and T 1 needs to be bidirectional. If you take the second state, the switch between P and T 1 or I mean on the switches between them are in the off state now and T 1 is positive with respect to P and you have a potential difference of V DC by 2. If you take the third state again the switches or the devices between P and T 1 are on the off state and they are blocking a potential. Earlier it was V DC by 2, now the potential is V DC.

So, this is what you need now you need a switch between P and T 1 which can conduct in both the directions and it can block a potential with this polarity as indicated here of you know with plus and minus of DC bus voltage, I mean the voltage equal to DC bus voltage now.

So, if you look at the second pole to throw 3, the story is same. When it is connected between pole and throw 3, you need a bi-directional conduction. When this pole P is connected to throw T 1, P is basically connected to the positive bus. T 3 is always connected to the negative bus and it has to block a potentially equal to V DC. Whereas, if you take this case again the polarity is the same it is blocking, but the voltage blocked is only V DC by 2 and V DC is higher of these 2.

So, if you take the pole P to the middle throw then what you have is slightly interesting. Again, when it is on, it has to conduct in either direction because the load current could be in either direction. When it is off and when P and T 1 are connected P is positive and this throw is negative and the potential coming between the 2 is V DC by 2. When pole P is connected to throw T 3, once again you know the devices between P and T 2 are in the off condition now, but if you look at the potential is the same V DC by 2, but if you look at the polarity it is now the opposite of what it was. Here, the throw is positive with respect to pole, earlier the throw was positive I mean the pole was positive with respect to pole.

So, what you need between P and T 2 is a 4 quadrant switch, this is what we saw in the last lecture. Whereas, between P and T 1 and P and T 3 what we need are 2 quadrant switches, which can block voltage of one polarity, but conduct in either direction.

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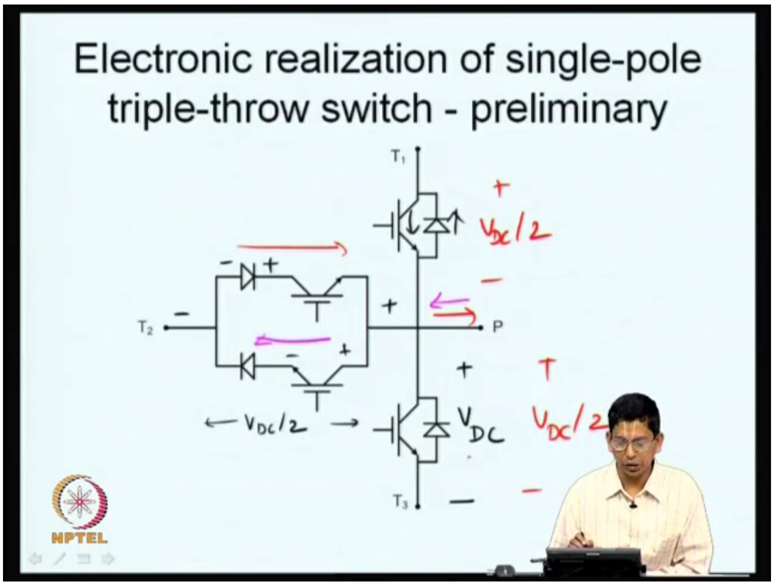

So, what you can have as a first cut realization is like this now. So, if you look at this; obviously, it can conduct in both the direction, the transistor can conduct in this direction on the diode can conduct in this direction when P and T 1 are to be connected. In such a scenario, you have the bottom switch, the transistor blocking a potential equal to V DC with polarity as indicated above.

Now, what you have is you have T 1 connected to P; therefore, P is connected to plus V DC. So, now, this is plus V DC by 2 with respect to the midpoint. Now, one of the switches should be blocking here and this is positive with respect to P is now positive with respect to T 2. So, if you take this path, this diode will be blocking and if you take this path, this transistor will be blocking. This potential equal to V DC by 2 here, this potential is V DC by 2.

Now, if you take now this is what when P is connected to T 1, the story will be similar when P is connected to T 3. In that case the bottom transistor or the diode will conduct depending on the direction of the load current and the top transistor will be blocking a potential equal to plus minus V DC and here again you may have a V DC by 2 blocked by the other transistor and the other diode as we observed before. If P and T 2 are connected together let us say P and T 2 are connected.

So, T 1 and T 2 are in the off condition, in such a scenario what we will find is, both these will blocking some potentials equal to V DC by 2 and the direction of current depends on you know the conduction depends on this direction of current. If I say this is the direction of current, then the current will flow through this arm. If I say the direction of current is different like here in the opposite direction then, current would flow through this branch. So, this is what will happen now.

So, here you know the situation is what we need is it is not enough if you have a blocking potential of V DC by 2 you need switches which can block up to V DC. So, this is what you know you still need a higher DC bus voltage rating. What we need to see is you know we want to use only switches whose voltage ratings are V DC by 2 basically.

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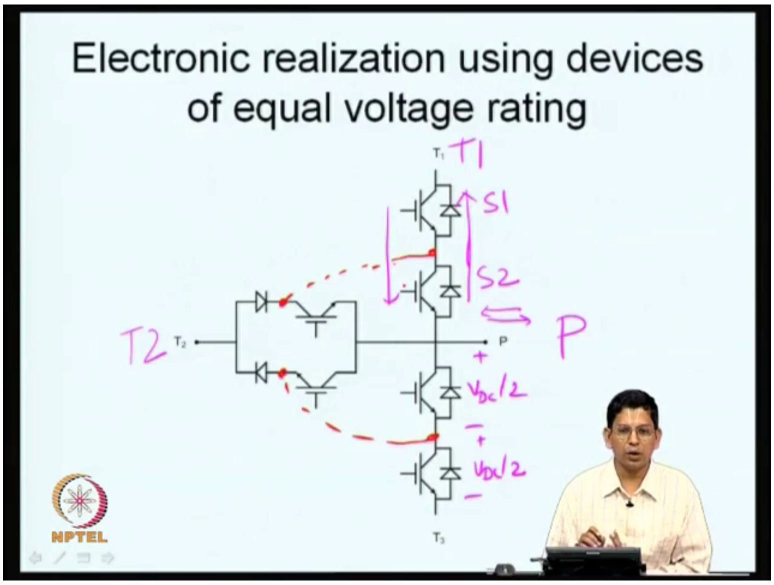

So what we do is, we connect 2 of them in parallel. In this situation let us say there is a current flowing it could be in either direction. In that scenario, current can be either flowing through the transistors or through the diodes we are presuming that P and T 1 are now connected.

And the bottom devices can be blocking potential of V DC by 2 each like this. Of course, this presumes that the voltage is shared more or less equally, but which need not be the case now. To some extent a multilevel converters configuration can help which we will see now. Before we go there, let us try and see whether we need all these transistors, we totally have 6 transistors do we need all these transistors is one of the questions we really want to see now.

So, that is where we come to this kind of a realization that can be seen from here. So, let us say P should be connected to T 2 this is pole P this should be connected to the throw T 2. In such a case pole P should not be connected to T 1. How do you ensure that? It can be ensured by having either 1 of the 2 top transistors, let me call them as S 1 and S 2, both of them could be off or even one of them could be off.

So, it is enough if one of them could be off and it is enough if S 1 alone could be off. So, if it is going to conduct if it is going to conduct for example, it is conducting to both these transistors now. So, both the transistors are not actually required to separate this T 2 from T 1, so let me say, why not make a connection like this. Let me consider these 2 points and let me say what happens if you connect these 2 like this. Nothing, because if P and T 2 are to be connected, if S 1 is turned off, there will not be any connection between P and T 1, only there will be a connection between P and T 2 and current will flow either through this diode and this transistor. So, there is no problem, it can conduct like this. Similarly, you can also make a connection like this on the lower side.

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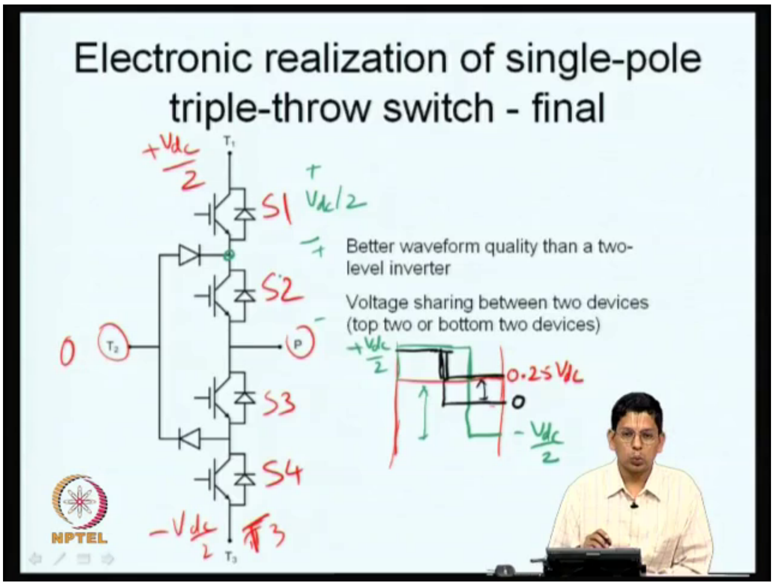

So, these 2 transistors are can actually be in parallel or they can be replaced by the same transistor by single transistor. So, you do not really need 2 different transistors and that is what you have as your usual realization. This one we call as S 1, this one we call as S 2, this one we call as S 3, this one we call as S 4. So, S 1 and S 2 will be on, for you to connect this pole P to top throw S 2 and S 3 will be on to connect pole P to the throw T 2 and S 3 and S 4 will be on to connect pole P 2, throw T 3 this is what we said now.

So, we have been saying that the waveform quality is better than that of a two-level inverter, let us see how. So, what you normally need is these potentials are we know this is plus V DC by 2, this potential is 0, this potential is minus V DC by 2. What we normally do with any switching converter is, at the pole we realize an average voltage which is somewhere between the voltages of the various throws. When in a case of a DC- DC converter, let us say a buck converter, we realize a pole voltage, average pole voltage which is somewhere between the DC bus voltage and 0. And here similarly, we will realize an average pole voltage which is somewhere between the voltages of throw T

1 and 0 or you know throw T 2 or between that of throw T 2 and throw T 3. That is, it can be anywhere between plus V DC by 2 and minus V DC by 2. If pole P is connected to throw T 1, I mean we are considering a small interval of time. We are considering, let us say, small interval of time this, what do you mean by small interval, this is much smaller than the fundamental modulating frequency that we are talking about.

The small interval of time if pole P is always connected to throw T 1, then the average voltage is plus V DC by 2. If it is always connected to throw T 3, then the average voltage is minus V DC by 2. If pole P is always connected to throw T 2, the average voltage is 0. Now, let us say, you have some potential like this; let me call this as 0.25 V DC. If I were to realize this 0.25 V DC using a two-level inverter what I would do is I will apply some plus V DC by 2 and for a long time and minus V DC by 2 for a shorter time. This is plus V DC by 2 and this is minus V DC 2. For roughly 75 percent of the time, if I apply plus V DC by 2 and minus V DC by 2, I get an average like this. This is the situation in a two-level inverter. If I consider a three-level inverter, what I can do is, I can apply either plus V DC by 2 or 0. I can apply plus V DC by 2 for half the time and apply 0 for another half the time.

So, this will also produce I mean the same average voltage I you know my 0 is not here actually, please ignore that mistake this is 0. So, I will apply plus V DC by 2 for half the time and 0 for remaining half the time. So, now, what do I get, I end up getting the same average voltage. So, I can get this 0.25 V DC by time averaging of 0.5 V DC and minus point 5 V DC. I can also get this 0.25 V DC by time averaging of 0.5 V DC in 0, which is better time averaging of 0.5 V DC and 0 is better. Why, because the maximum error that you have between the ideal waveform which is equal to 0.25 V DC, that is what you want and the actual waveform which is what you apply is now much lower.

So, if you consider this the error is only so much. In a three-level inverter. Correspondingly, if you had considered a two-level inverter, the error is substantially higher. So, the instantaneous error between what you want, that is, the average voltage and what you apply, that is, the actual instantaneous voltage is higher in a two-level inverter and is lower in a three-level inverter, therefore, three-level inverter can actually give you better waveform quality.

So, also as we said you know voltage sharing is better now the in a entire DC bus voltage is blocked. When it needs to be blocked it is not blocked by single device, but by both the devices let us say S 1 and S 2 or the devices S 3 and S 4. Now, they also contributes to certain amount of voltage sharing. See S 1 and S 2, if they are blocking a potential equal to V DC it is not necessary that they should block equal voltages, they should share the voltage equally the voltage sharing could certainly be unequal.

Now, here let us consider this node. Whenever this node goes below 0, the diode will come into conduction that will force that this potential stays within V DC by 2. This potential when S 1 and S 2 are blocking, it will make sure that this potential stays within V DC by 2. It will not let the potential really go above that. So, some kind of check is being exercised on the voltage sharing between these 2 devices. So, multi level converter is better than basically 2 transistors with you know connected in series for voltage sharing.

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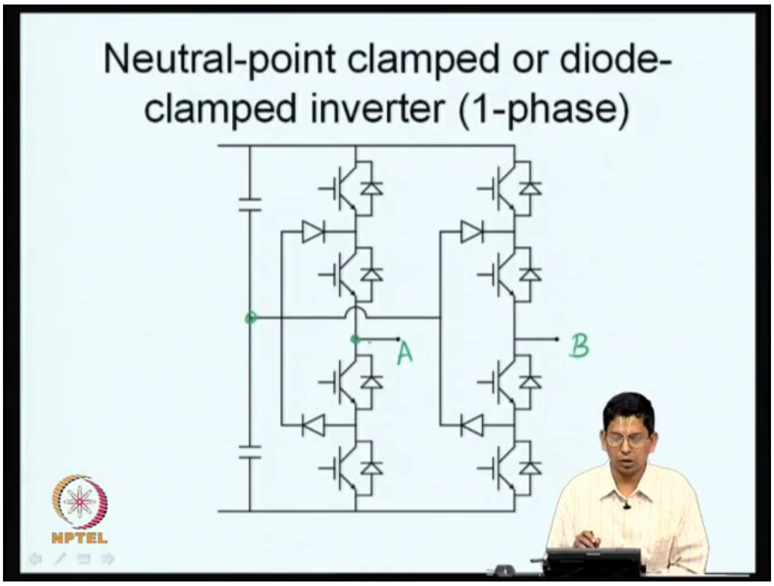

So, let us say, we move on to this is one leg. This is just one leg of that; if you put 2 such legs together let me call these terminals as A and B, so, this becomes a single phase multilevel inverter or a single phase three-level inverter. It is called neutral-point clamped or a diode clamped inverter, as we mentioned before, because what we mean by neutral is the DC bus neutral. This DC bus neutral could be connected to the phase or the output terminal or the midpoint of a leg. So, you call it neutral point clamping and you use diodes to do this kind of a clamping, you may connect either through this diode or this diode. So, you call it as a diode-clamped inverter 2. So, this is the name that it normally goes by. If you want a 3 phase inverter, what you need to have is, one more leg like this is necessary. You have a third leg and the 3 terminals the load terminals can be connected to the midpoints of the 3 legs R, Y and B.

So, this is now diode neutral clamp inverter.

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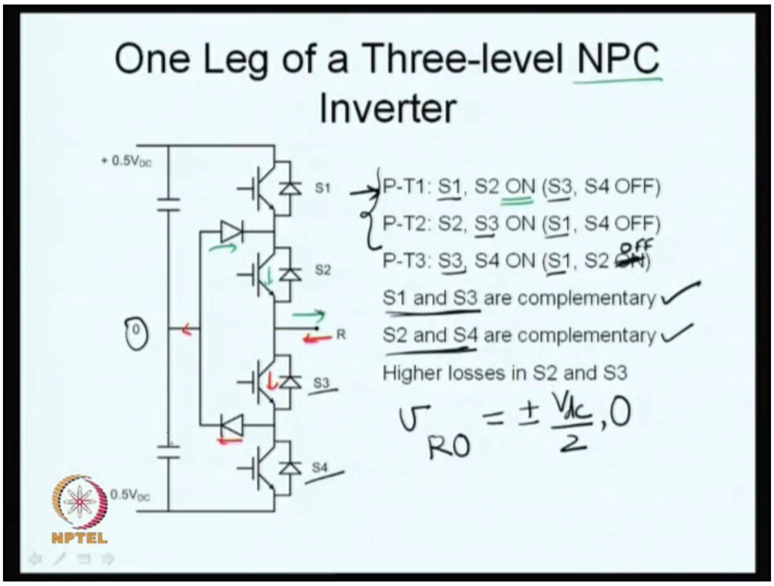

Now, we are just kind of summarizing a few points and understanding a three-level neutral-point clamped inverter better. NPC is the abbreviation for neutral-point clamped inverter. Now, let us say if pole P is connected to throw T 1 that is the first state. In that case we find that S 1 and S 2 are in the on state, the top 2 devices are in the on state.

So, it also means that S 3 and S 4, the bottom 2 devices are in the off state. S 4 has to be off. S 3 also has to be off. If S 3 is not off then there is a possibility that the pole may get connected to 0. Similarly, when pole P is connected to throw T 2 then S 2 and S 3 should be on. So, depending on the direction of load current if the load current flows in this direction, the conduction will be between through this diode and through this transistor. On the other hand, as I mentioned before if the load current is in the opposite direction, then it will flow through this transistor and here and into the DC bus midpoint.

So, in such situations S 2 and S 3 will be on and S 1 and S 4 will be off. This will prevent the pole from getting connected to either the top throw or the bottom throw. Now, let us say pole P and T 3 are connected together, that basically means the bottom 2 switches S 3 and S 4 are now on, and the top 2, S 1 and S 2 are off. So, whenever you see S 1 is on you see S 3 is off. Here you see S 3 is on, S 1 is off. Here again you see S 3 is on and I am sorry this should be off there is a mistake here. So, this should be off this should be off.

So, S 3 is on and S 1 is off. So, S 1 and S 3 are complementary. S 1 and S 3 are switched in a complementary fashion, when S 1 is on S 3 will be off and vice versa. Similarly, let us say we have S 2 and S 4. Whenever you find S 2 is on, when will S to be on, S 2 will be on whenever you need to connect the pole to the top throw or to the middle throw. Whenever S 2 is on S 4 will be off, when S 4 should be on? S 4 should be on when pole P is connected to the bottom throw. S 2 should be on whenever the pole P has to be connected to the top throw or the middle throw, S 4 should be on whenever it should be connected to the pole should be connected to the bottom throw. You see that they are mutually exclusive. So, S 2 and S 4 are complementary.

Similarly, S 1 and S 3; S 1 should be on only when the pole P is connected to the top throw, S 3 should be on whenever the pole P has to be connected to the middle throw or to the bottom throw. So, S 1 and S 3 are complementary. Similarly, S 2 and S 4 are complementary. So, these are certain things we see now. In a two-level inverter we had only 2 transistors. So, they need gating signals and they are switched in a complementary fashion. So, effectively you needed only one independent gating signal. How about a three-level inverter? In three-level inverter you need 2 gating signals, maybe for S 1 and S 2 or S 1 and S four. So, S 3 can be generated as the complement of S 1 and S 2 or S 4 can be generated as the complement of other. So, you need 2 different gating signals.

Now, we have not really come up with a proper framework for calculating losses which will do it much later, but nevertheless we have some idea of losses. Let us try and see. How the losses will be different in different devices etcetera.

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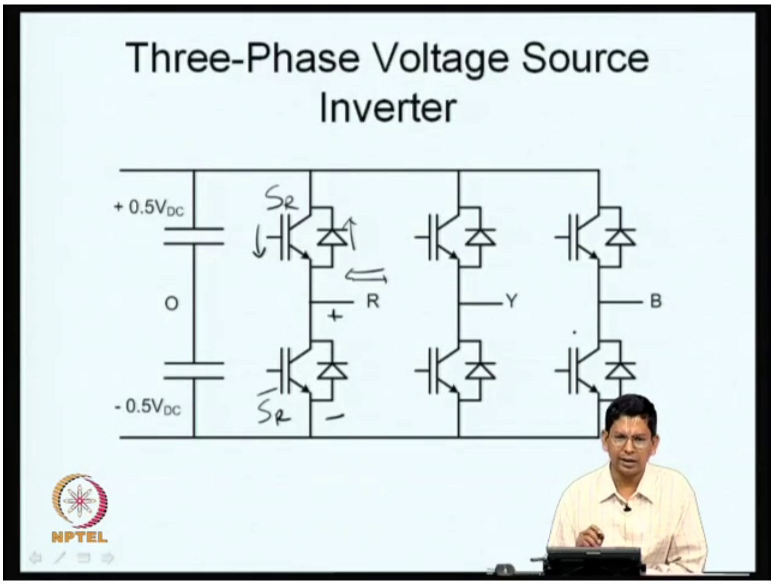

If you take an earlier two-level inverter, let us go back to one of the two-level inverter. Now, this is a two-level inverter now. In this, can we say that the losses in all the 3 legs will be equal? Yes. Why, because we will be controlling them in a we assume all balanced conditions. There is a DC bus voltage and the load is balanced and we are controlling it in a balanced fashion.

So, all the 3 legs will have equal losses and the loss in every leg is due to both the top and the bottom device. On the top you have a transistor as well as diode and so on and the losses can be split into either conduction or switching loss. So, the conditions are identical now. So if a particular phase has a peak current now, the next phase will see the peak current some another 120 degrees later and the third phase will see the peak yet another 120 degrees later. So, they are in a balanced condition and therefore, they get heated to be equal this thing. There are some modulating methods which will lead an unequal loading of top and bottom, as we will see some time when we are looking at this bus clamping PWM or discontinuous PWM, but we are by enlarge use such modulation methods which load the top and the bottom equally.

So, all of them will be loaded to an equal extent. So, if the top transistor conducts for certain length of time, the bottom transistor will also conduct for an equal length of time. So, and again the total losses will kind of be equal between the 2. Basically, which is because of the symmetries, as long as you have a symmetries between the 3 phase and every phase is half wave symmetric, there is some symmetry between the positive of cycle and the negative cycle. The top and the bottom devices they also will have equal losses now. But, the situation is a little different when you go to a multilevel inverter let us see how.

Now, in this situation, let us just consider S 1 and S 2. When will S 1 be on? S 1 will be on, whenever you have to connect the pole P to the top throw T 1, this alone is a situation when S 1 has to be on. When should S 2 have be on? S 2 needs to be on, whenever pole P is connected to the throw T 1 or pole P to throw T 2. So, naturally S 2 is on for longer duration than S 1. So, whenever pole P is connected to throw T 1, S 1 is conducting and the transistor S 2 could also be conducting. Well, it could be the diodes too; the corresponding diodes metal should be conducting.

But whenever pole P is not connected to throw T 1, neither the transistor S 1 nor the corresponding diode will be conducting, but when pole P is connected to throw T 2, half the time roughly transistor S 2 or transistor S 2 will conduct or for another half the time transistor S 3 will conduct. So, S 2 can conduct I mean it does conduct whenever pole P is connected to throw T 1 and it also conducts part of the time, whenever pole P is connected to throw T 2, depending on the load direction. If the load direction is as indicated by the green line you know S 2 conducts now.

So, what can we say S 2 is going to conduct for longer, so its conduction losses certainly higher now. So, the same argument can be made out between S 3 and S four. So, you can see that the losses in S 2 on S 3 are likely to be a little higher than the losses in the other 2 extreme devices now. So, this is something that we can make out in a very fairly qualitative fashion. So, we will evaluate losses particularly in the case of a two-level inverter much later in this course and that will also give us a necessary background to actually evaluate losses in a three-level inverter. Now, we are just trying to see qualitatively how these things are affecting now.

So, you normally find the middle 2 devices probably suffer a greater amount of loss that is what you should expect at this point of time now. What I want to say is, this is not the only way a three-level inverter can be realized. What do we mean by three-level inverter? I have this pole, which I call as R which is same as the R phase terminal and then that pole there is a voltage at that pole V, at R measured with respect to O being the DC bus midpoint.

Now, a three-level inverter can produce I mean value of V RO which is either plus V dc by 2 R minus V dc by 2 as in the case of a two-level inverter and also 0. So, this is how it is different now. Can we have other possibilities? Rather than what we have come up with as you know three-level neutral-point clamp inverter which can give you these values of V RO being 0 also in addition to plus or minus 0.5 V dc. That is what we are going to see. One alternative that we can think of is, a flying camp flying capacitor inverter which we come to here now.

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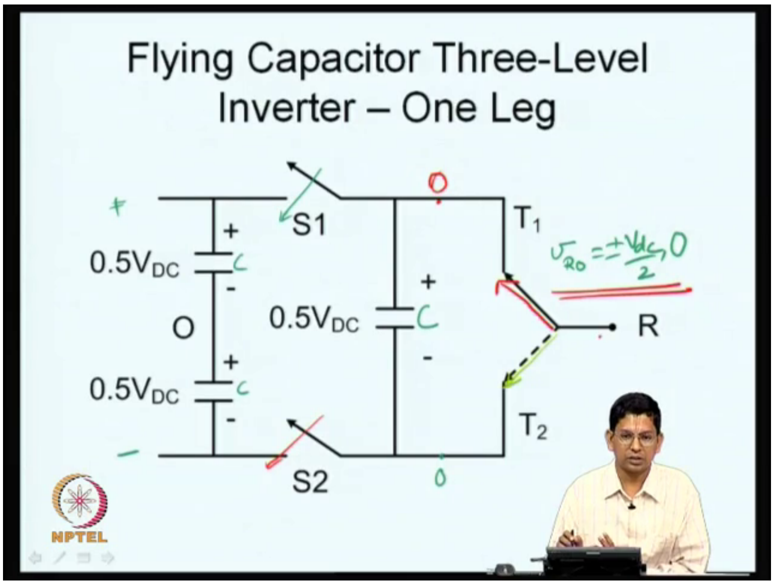

Before that let us just see will go to some higher levels of multilevel inverter now.

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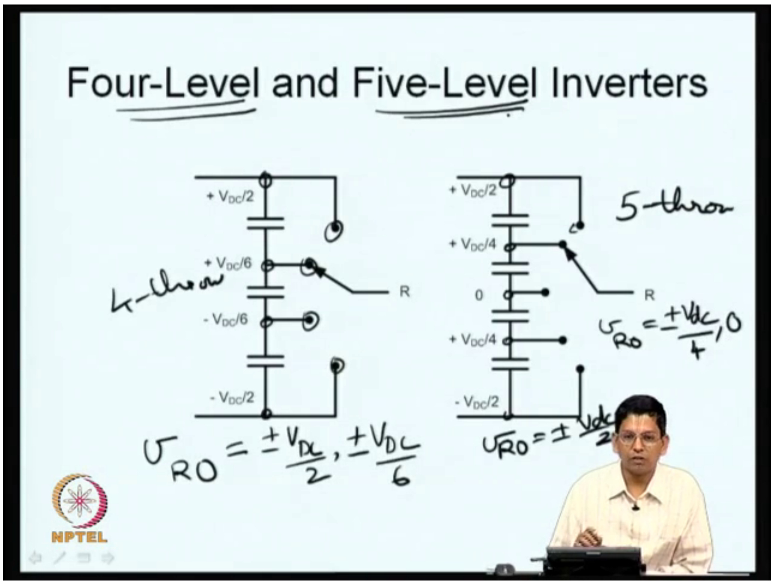

So, this is called a four-level inverter. It is called a four-level inverter, because you know you have 4 different potentials available here. There are 4 different nodes, 4 different potentials available and then you have 4 different throws. You have 1, 2, 3, 4. So, it is a single pole 4 throw switch and the 4 throws are connected to 4 different potentials.

So, here, your V R O being the midpoint which is not indicated explicitly here. O is really the midpoint which is really the average of the 2 extreme potentials. If you look at your V R O. It can be plus or minus V DC by 2. If R is connected to the top throw or bottom throw you get plus V DC by 2 minus V DC by 2, as in a two-level inverter. In addition to that you also get potentials plus or minus V DC by 6. If R is connected to the second throw or the third throw you get potentials plus V DC by 6 or minus V DC by 6 respectively. So, this is a four-level inverter, your pole voltage has 4 different levels now.

Similarly, you can also have a five-level inverter. In this case you see that there are 5 different potentials 1, 2, 3, 4 and 5. These are connected to 5 different throws and you have a single pole 5 throw switch here. Here you have a 4 throw switch here; you have 5 through switch now. So, here you have your V RO equal to several values. It is equal to plus or minus V DC by 2 as you would normally have in a two-level inverter. In addition, V RO can take values of plus or minus V DC by 4 also. If it is connected here are there and of course, it can also take the value 0.

So, it can take 5 different values plus or minus V DC by 2 plus or minus V DC by 4 and 0. So, you call this as a five-level inverter now.

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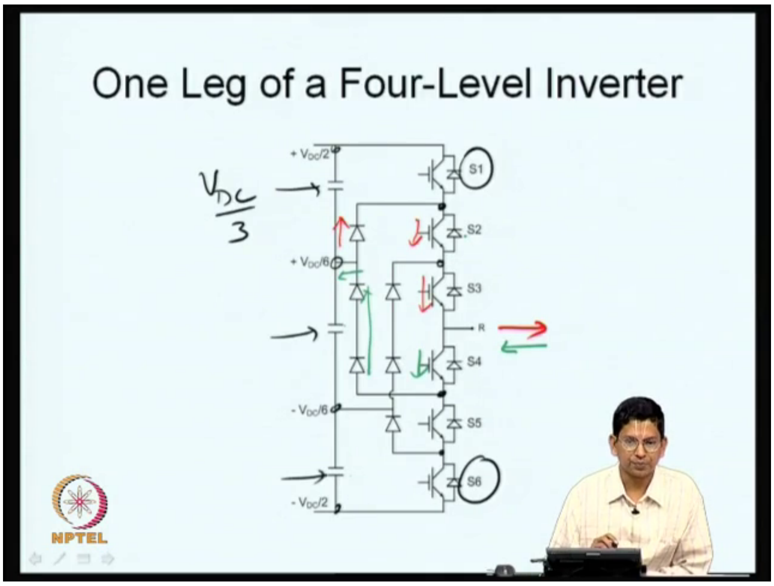

So, how do you realize these four-level and 5 level inverters is a question. So, it is actually a single pole 4 throw switch and you can come by realizing it one by one follow the same steps that we followed in a single pole triple throw switch. So, what you will now get is, you see that there are earlier we had 4 transistors here, now, we have 2 transistors more at the extreme ends this is what we have.

And also you have instead of 2 different sets of series capacitors you have 3 sets of capacitors and the capacitors carry a voltage equal to V DC by 3. So, 3 sets of capacitors each support a voltage at V DC by 3 together it adds to the total DC bus voltage V DC. So, these points 1, 2, 3, and 4 points are connected now. So, the middle 2 points particularly plus V DC by 6 and minus V DC by 6 are connected through a set of diodes. Either to one of these intermediate points, these intermediate points here, they are connected there and so they then through the other transistor or the diode they can conduct to R for example.

So, you have a single pole 4 throw switch realized here. For example, if you will if you say R is conducting in a particular direction. If let us say the current is flowing in this particular direction and let us say pole has been connected to V DC by 6 this throw, then the current can flow through this diode through this transistor and through this transistor and can flow out now.

Let us take another example that is the current is flowing in the opposite direction now in the opposite direction and it is connected to the same the pole is connected to the same throw. In such a scenario, it will connect through the bottom transistor and will go up through these 2 diodes will go away. So, that is how the direction of current flow is. Similarly, you can see this situation you can study the situation where the pole is connected to the other throw which is equal to minus V DC by 6.

So, every time you increase that some 2 more transistors get increased and voltage level gets increased by one more. You have one additional set of series connected capacitor. In case of three-level inverter you had 2 sets of capacitors in series. In case of a four-level you have 3 of them in series. If you go to five-level you will have 4 of them in series now.

So, then you have more number of transistors and you also have diodes which will go and clamp them or connect them to the appropriate nodes. So, this is how you have a four-level inverter if you want to go for a 5 level inverter, it just goes up like this now. So, this is very popular all these are diode clamped inverters. So, they are used diode for clamping.

The alternative option that I was trying to say to realize V RO is of different values. This is also an inverter where I can realize V RO equal to plus or minus V DC by 2, as in the case of a two-level inverter and also 0 this is another thing. What do I do here? I use to charge capacitors. So, there are 2 sets of capacitors which are charged in series to voltages, I mean they are charged to voltage levels of V DC by 2. These 2 sets of capacitors are in series now, they are supported, they are fed from some voltage source here of plus minus as I have indicated here now.

So, these 2 are firmly connected their terminals are firmly connected to a voltage source let us say. Now, we have yet another capacitor, the same value c, let us call this values as c and it is also charged to plus 0.5 V DC with polarity as indicated here now. So, what I can do is, if I add this if I use a switch like this S 1 and close the switch then the potential at this point, this is the potential at this point will be equal to 0, if this switch is closed.

So, alternatively, if let us say this switch is closed this closed then the potential here would be 0. So, what we are trying to do is, we are trying to realize multiple voltage levels by connecting charged capacitors in series. So, we have one charged capacitor of 0.5 V DC we are trying to connect this in series now. So, you know this 0, it can be taken in by using a single pole double throw switch as indicated here.

Now, let us say R needs to be connected to just the positive bus. All that you need is R has to be connected to the top throw as here and S 1 is closed. If R has to be connected to the bottom throw, then what you need to do is, R can be connected to T 2 here and S 2 can be closed. Then that will be connected to the bottom throw. If R has to be to the negative DC bus, if R has to be connected to the DC bus midpoint you are not connecting it to the DC bus midpoint exactly, but what you are trying do is you are doing a series connection like that you are closing S 1 and so that the potential here is 0 and you can close this switch.

So, this combination this switch closed means this midpoint is equal to 0 and you can put this single pole double throw switch can be connected to the bottom throw. So, this gives you a potential equal to 0. You can get this potential equal to 0 and another way also as indicated by the red one this switch S 2 can be closed. Of course, S 1 has to be opened now, S 2 is closed. So, in that case what happens, the potential here is 0. So, this is kept in the on condition, this switch is kept in the on condition. So, you can apply 0.

So, if R has to be connected to the positive DC bus, there is only one way of doing. The pole has to be connected to the top throw and S 1 has to be closed. Of course, S 2 has to be opened, if pole P has to be connected to the negative DC bus, I mean, the R phase terminal again, it is unique. Pole has to connect to the bottom throw and S 2 has to be closed, but if the pole has to be connected to the DC bus midpoint or should be connected to the DC bus neutral potential equal to the DC bus neutral, there are 2 different ways for V RO is equal to 0 you can connect this pole to the top throw and the bottom switch S 2 can be on here or alternatively switch S 1 can be on and this pole P can be connected to the throw T 2.

So, these are 2 different ways by which you can realize this. So, here also you are getting V RO is equal to 0 in 2 different base now. So, you are getting V RO is equal to 0, just in the case of a three-level inverter. That is possible now in 2 different ways. Now, we have to see, how do we realize this switch. So, if you have such switches you can you know it is possible to produce V RO is equal to plus or minus V DC by 2 and also V RO is equal to 0. So, it is the same as are equivalent to a three-level inverter you are able to apply 3 different potentials at the pole now.

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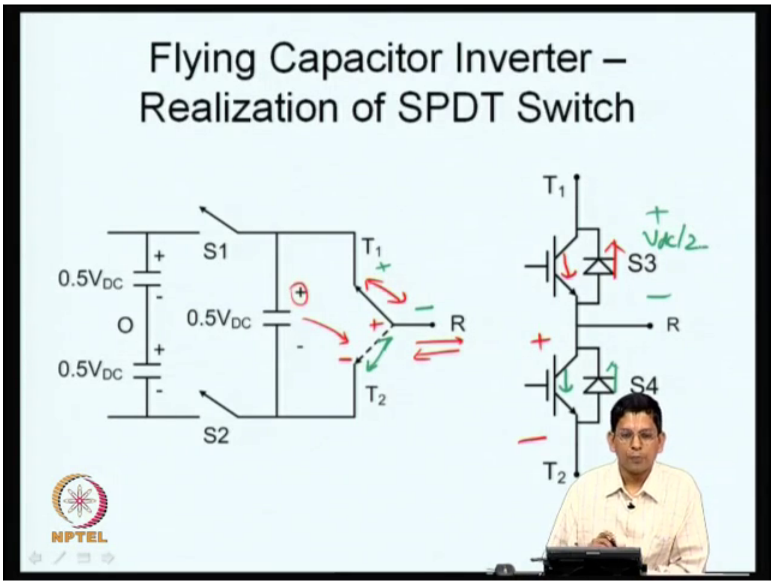

So, how do you realize the switches that is the first question now. Let us first look at how S 1 and S 2 can be realized. Now, what is going to be the direction of current flow? It is an AC load. So, current can be flowing in either direction. So, if you consider switch S 1; S 1 is closed, S 2 has to be open, because you know you see the series potential here is V DC whereas, the potential here is only V DC by 2 therefore, closing S 1 and S 2 is not possible. If S 1 is closed, S 2 has to be open or vice versa, but at least one of them has to be closed otherwise the DC bus capacitors will be totally isolated from the pole voltage. So, 1 of them will have to be closed to make a connection now. So, either S 1 is closed or S 2 is closed now.

So, let us consider the situation S 1 is closed. If S 1 is closed then your direction of conduction depends on the load current. It can be conducting either from the left to right or right to left, as I have shown here now. So, the switch S 1 has to be a bidirectional current carrying switch. Now, how about S 2 correspondingly, now what we have done is S 2 this side potential is equal to 0 whereas, this side potential is equal to negative. So, S 2 is actually blocking a potential which is plus on this side and minus on this side and the potential is equal to V DC by 2. The same scenario, if you consider that S 2 is on if S 2 is on this will be conducting in one of the 2 directions, depending on the load current and here it will be blocking a potential with such polarity. S 1 will be blocking potential with this polarity now, because this is closed. Here, the potential is equal to that of the positive terminal; this side the potential is equal to that of the DC bus midpoint. So, the potential difference is V DC by 2 with polarity as indicated now.

So, this is what perfectly fits on. So, what you need is you get a bi-directional current carrying switch and a voltage blocking capability as shown here. The same way for S 2. So, you just basically use an IGBT with an anti parallel diode that serves the purpose for S 1 and S 2.

Now, what we need to do is, we need to look at how to realize this single pole double throw switch. So, as we said before the current is bidirectional, therefore, if the pole is connected to the top throw this the devices between the pole and top throw or whatever switch comes between there has to have a bidirectional current carrying capability. So, when that is there, what happens here is this potential is, now connected to the top throw and therefore, to the positive terminal of this capacitor. So, this comes here and this connects to the negative terminal of the capacitor. So, this is equal to minus and the potential difference is the same as what you have here. This capacitor voltage comes across the pole on the throw.

So, this is what you get by having 2 transistors like this. You have a transistor and an anti parallel diode. So, that they have a bidirectional current carrying capability now the bottom transistor can block a potential like this now. On the other hand, let us say, you have pole connected to throw T 2; if pole is connected to throw T 2, then this has to be bidirectional current P and T 2. Between P and T 2, you need a bidirectional current carrying capability.

So, that is what you have now. So, when pole is connected throw T 2, then the top throw is positive now with respect to the bottom throw and it is blocking a potential equal to V DC by 2. It is blocking a potential equal to V DC by 2. So, this is what you have now. So, a single pole double throw switch can be realizes just the same as what we had in a let us say voltage source inverter or so.

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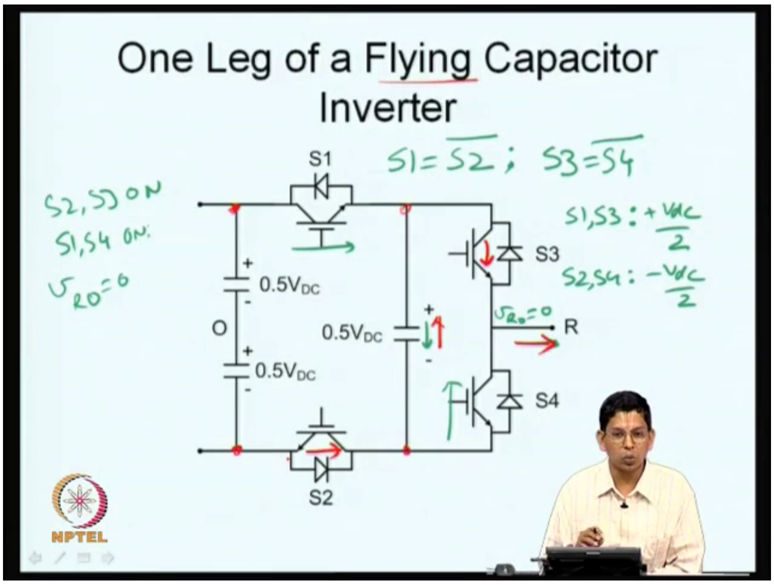

So, this is how you realize this and we put together. All the realizations S 1 and S 2 are basically IGBTs with the anti parallel diodes and the single pole double throw switch is basically like this S 3 and S 4. This is one leg of a flying capacitor inverter. You can have yet another leg and then it I mean 2 legs to make a single phase inverter. You can have 3 such legs to make a 3 phase inverter now.

So, now the rules are very clear S 1 and S 2 are complementary. S 1 is equal to S 2 bar. If both are open, there is no power. The DC side is totally isolated from the load side now. It does not function. The inverter is not functioning, there is no power flow there if both are on you are shorting capacitors charged to V DC by another set of capacitors charged to V DC by 2 which you cannot be doing. So, S 1 and either if S 1 is on are you know S 2 is on the other one should be off now. So, S 1 and S 2 are complementary and of course, S 3, S 4 basically you know it is actually a realization of single pole double throw switch. Therefore, you also have S 3 is equal to S 4 bar. This is how you operate the switch now.

So, here again you need to gating signals. Let me say S 1 and S 3. From S 1 you can generate S 2, from S 3 you can generate S 4 and you have V RO is equal to various values. V RO can be equal to plus 0.5 V DC. If S 1 and S 3 are on, if S 1 and S 3 are on then your V RO will be equal to plus V DC by 2. If you are S 2 and S 4 are on then your V RO will be equal to minus V DC by 2. The other hand if you have your S 1 and S 4 on, if you have S 1 and S 4 are on then what happens is, you get 0. This potential is now effectively 0. So, V RO is equal to 0 the same thing can be realized by having S 2 and S 3 also on.

Now, let us say the current can actually be bidirectional. So, here let us say you are having V RO is equal to 0, now let us say this has been achieved by having these 2 switches S 1 and S 4 on. So, the current conduction will be like this. This is how the current will be conducting. Now let us say you want V RO is equal to 0 and the same direction of conduction, but by S 2 on S 3 are on now. So, what you will have is, you will have sorry. So, this would be the direction of current flow. This you ignore that, let me erase with a eraser. So, what you really have is, the current actually flows in this direction through the transistor and it flows out.

So, in one if for one set of switches the capacitor charges and the other set it discharges. So, what we need to do is we will actually apply V RO in one fashion and the other fashion alternatively, to make sure that the capacitor does not get discharged and you see that this capacitor its terminals are not connected to any firm potential whereas, this capacitors terminals are connected to firm potential. These 2 are actually connected to some DC supply. So, they connected to firm potentials and this is just a series connection of capacitors now and if you look at here, what do we have, the neither of these 2 terminals are connected to any firm potentials, they are actually connected to switches. Now, therefore, you get the name flying capacitor. Basically, the capacitors terminals are not connected to form potentials now it is floating or it is flying capacitor inverter now.

So, you have a unique way of connecting the pole to the positive DC bus or the negative bus, but if you look at the intermediate potential namely V RO is equal to 0, you have multiple ways of doing this and these multiple ways of doing this help you maintain the charge on the capacitor. In flying capacitor, this is certainly a challenge for you to first have the capacitors charged to this voltage level and continue to maintain that the capacitors remain charged and this voltage levels now. So, it has to be modulated and it has to be controlled in an appropriate fashion that these capacitor voltages are reasonably at 0.5 V DC that is what we have been trying to say.

So, there was an additional point that we really had to make about a three-level inverter now. If we say in a three-level inverter in a three-level inverter we see that the current here actually flows into the DC bus neutral. In a two-level inverter where does the current flow? The current only the ripple current here flows.

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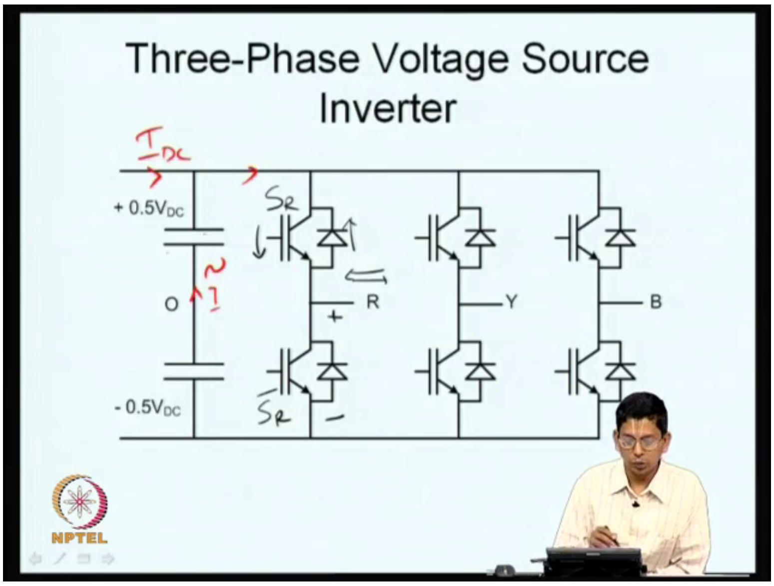

One of the early slides if you look at, where we looked at this or maybe we can take this here. So, you will have some current and what flows through is will only be ripple here, we will call it as some I tilde also this is some I DC, is the sum of these 2 this is going to flow here. It is only a ripple that flows through that.

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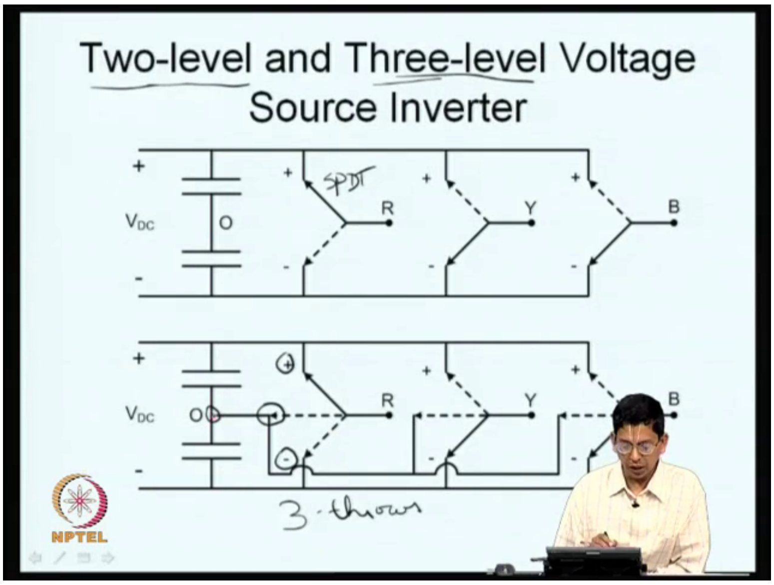

Now, what happens, there is no actual DC current or anything flows through that in the case of a three-level inverter, because you are connecting it to the midpoint. The load current sometimes flows through the DC bus neutral, because of this you can have a situation where the top DC bus is charged or discharged in a particular fashion.

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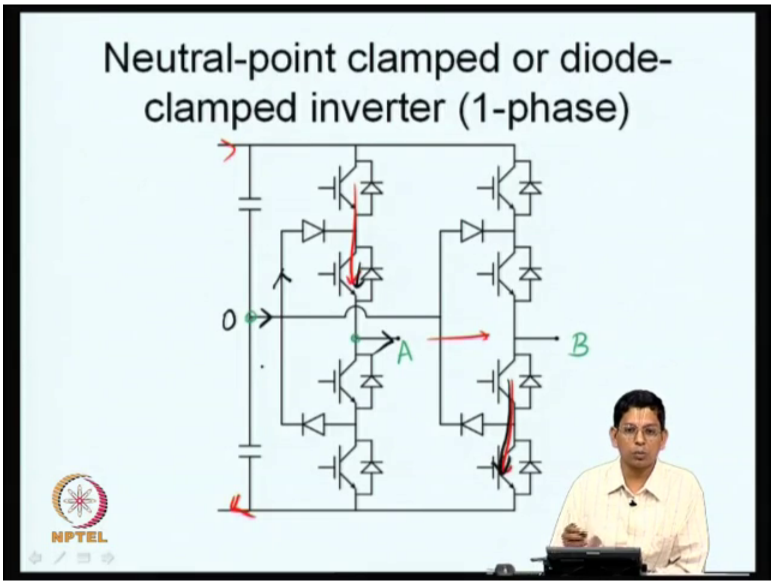

Now, let us say, you have this like this now. If the load, if your poles are connected only to the top throw or the bottom throw then the load current has, let me say, that the top 2 are on now, so they are conducting like this and there is a current flowing like this and then this is how the current flows. So, it flows out. So, this is how the current is flowing. So, there is no load current really flowing through the capacitors.

On the other hand, let us say, you have A connected to the midpoint. A connected to midpoint, that is, this O. So, in that case you know for a particular direction of current if I look at current can be flowing in this direction and let us say B is connected to the bottom throw. In that case current is flowing like this, through the 2 transistors and flowing back here. So, you see that there is certain amount of current which flows through those DC bus capacitors. The load current is now flowing through the DC bus capacitors. So, there is going to be a substantial charging and discharging now. The advantage of a three-level converter itself lies in the fact that it gives you better waveform quality, that is, basically you are able to connect the pole to the midpoint, that also provides you a disadvantage namely the DC bus is going to be balance could be lost.

You need good modulation and control methods to really come up with that. So, that is something you look at when we are doing modulation of DC bus this thing. Now, let us just quickly go towards the end.

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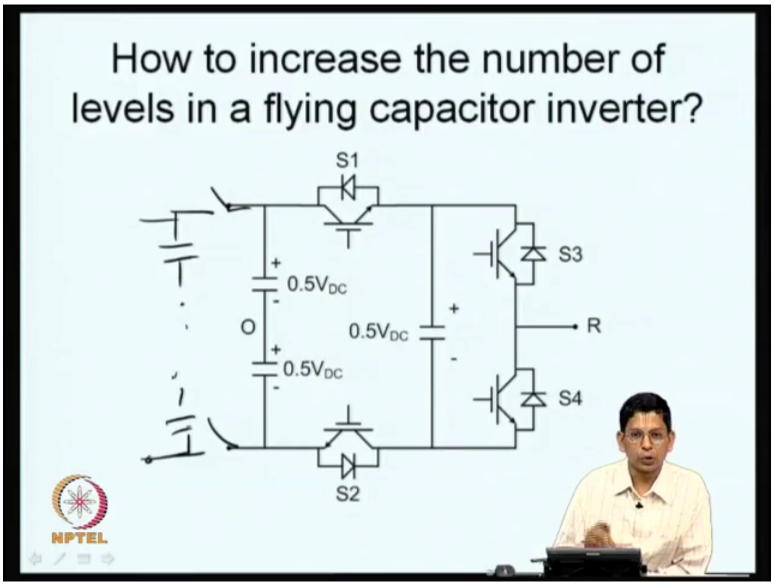

So, this is what one leg of a flying capacitor converter that we had. So, if you want to go increase the number of levels, how do you do that I just leave that to you. What you basically need is, just as an exercise you need more switches and you will need more stages of capacitors, how many stages, how many switches etcetera, I would leave them to you.

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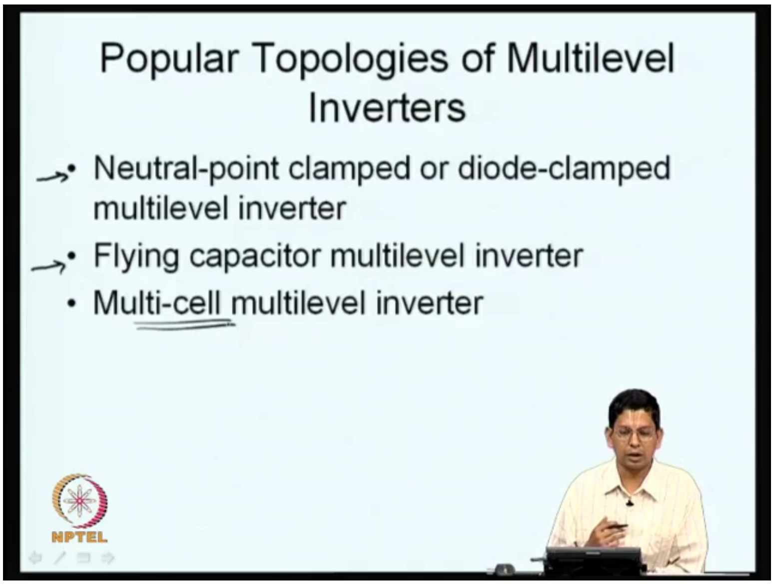

So, it is possible for it to once again come up like a three-level, four-level, five-level etcetera and to quickly summarize this neutral-point clamp or diode-clamp multilevel inverter is what we have been discussing extensively and what we will use in this course. We also discussed flying capacitor. Now this multi-cell is about using 2 single phase inverters for one leg you know a single phase inverter can produce some voltage output which is equal to 0 or the input voltage or the negative of the input voltage. So, you can have 2 of them connected connect them in cascade. So, 2 of them can series, connection can give you some number of voltage levels.

So, it is also possible to realize multilevel inverters using several single phase inverters, 2 single phase inverters, for example; in one leg. So, those are the 3 important ways, but our focus will be primarily on neutral-point clamped in this course now. So, I thank you very much for your attention and in the subsequent classes you will start discussing more about modulation. Before you go into modulation, we will quickly look at the various applications of voltage source convertors in the next lecture.

Thank you very much.